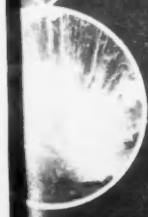
Atomic Power

CHEMISTRY

TEMBER
1945



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★ A SCIENCE SERVICE PUBLICATION ★

Atomic Energy

▶ THE WAR DEPARTMENT has released and authorized for publication the report by H. D. Smyth, Chairman of the Department of Physics of Princeton University and Consultant to Manhattan District United States Corps of Engineers, entitled "A General Account of the Development of Methods of Using Atomic Energy for Military Purposes Under the Auspices of the United States Government 1940-1945."

The editors of CHEMISTRY have found this report so epoch-making that they feel they owe it to their readers to devote this, the earliest possible issue of the magazine, to quotation of as many excerpts as space will permit. This report marks the beginning of our understanding of the realities the Atomic Age has in store for peace. Dr. Smyth explains the object of the report in his

PREFACE

▶ THE ULTIMATE responsibility for our nation's policy rests on its citizens and they can discharge such responsibilities wisely only if they are informed. The average citizen cannot be expected to understand clearly how an atomic bomb is constructed or how it works but there is in this country a substantial group of engineers and scientific men who can understand such things and who can explain the potentialities of atomic bombs to their fellow citizens. The present report is written for this professional group and is a matter-of-fact, general account of work in the United States since 1939 aimed at the production of such bombs. It is neither a documented official history nor a technical treatise for experts. Secrecy requirements have affected both the detailed content and general emphasis so that many interesting developments have been omitted.

References to British and Canadian work are not intended to be complete since this is written from the point of view of the activities in this country.

The writer hopes that this account is substantially accurate, thanks to cooperation from all groups in the project; he takes full responsibility for such errors as may occur.

July 1, 1945 H. D. SMYTH

CHEMISTRY

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Consulting Editor: PAULINE BEERY MACK (Editor 1927-1944.)

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Science Service is the educational and scientific institution organized in 1921 as a non-profit corporation with trustees nominated by the National Academy of Sciences, the National Research Council, the American Association for the Advancement of Science, the E. W. Scripps Estate and the Journalistic Profession.

▶ HOLOCAUST *at Hiroshima after the atomic bomb had found its target. This photograph by the U. S. Army Air Forces was made at an altitude of 25,000 feet.*

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than 20,000 tons of T.N.T. It had more than two thousand times the blast power of the British "Grand Slam" which is the largest bomb ever yet used in the history of warfare.

The Japanese began the war from the air at Pearl Harbor. They have been repaid many fold. And the end is not yet. With this bomb we have now added a new and revolutionary increase in destruction to supplement the growing power of our armed forces. In their present form these bombs are now in production and even more powerful forms are in development.

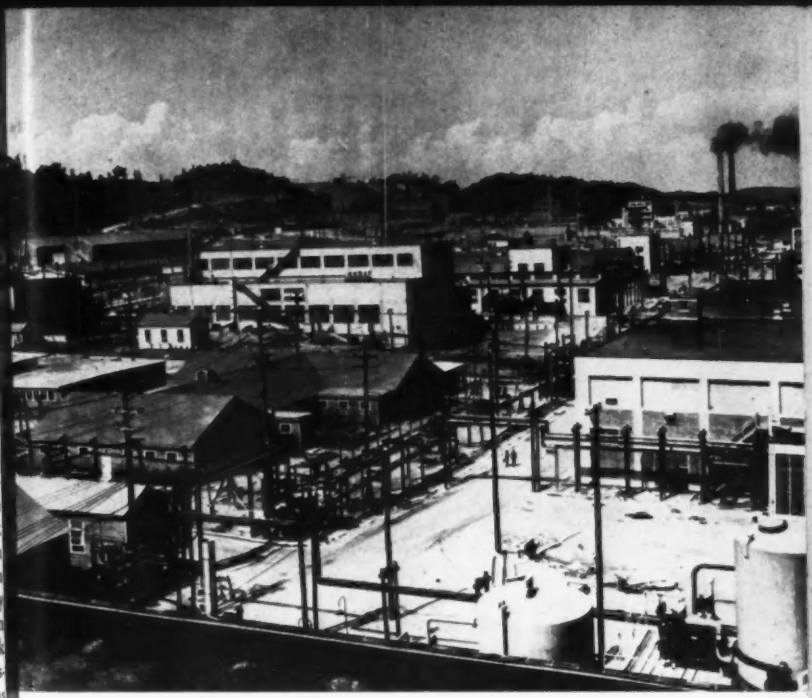
It is an atomic bomb. It is a harnessing of the basic power of the universe. The force from which the sun draws its power has been loosed against those who brought war to the Far East.

Before 1939, it was the accepted belief of scientists that it was theoretically possible to release atomic energy. But no one knew any practical method of doing it. By 1942, however, we knew that the Germans were working feverishly to find a way to add atomic energy to the other engines of war with which they hoped to enslave the world. But they failed. We may be grateful to Providence that the Germans got the V-1's and the V-2's late and in limited quantities and even more grateful that they did not get the atomic bomb at all.

The battle of the laboratories held fateful risks for us as well as the battles of the air, land and sea, and we have now won the battle of the laboratories as we have won the other battles.

Beginning in 1940, before Pearl Harbor, scientific knowledge useful in war was pooled between the United States and Great Britain, and many priceless helps to our victories have come from that arrangement. Under that general policy the research on the atomic bomb was begun. With American and British scientists working together we entered the race of discovery against the Germans.

The United States had available the large number of scientists of distinction in the many needed areas of knowledge. It had the tremendous industrial and financial resources necessary for the project and they could be devoted to it without undue impairment of other vital war work. In the United States the laboratory work and the production plants, on which a substantial start had already been made, would be out of reach of enemy bombing, while at that time Britain was exposed to constant air attack and was still threatened with the possibility of invasion. For these reasons Prime Minister Churchill and President Roosevelt agreed that it was wise to carry on the project here. We now have two great plants and many lesser works devoted to the production of atomic power. Employment during peak construction numbered 125,000 and over 65,000 individuals are even now engaged in operating the plants. Many have worked there for two and a half years. Few know what they have been producing. They see great quantities of material going in and they see nothing coming out of these plants, for the physical size of the explosive charge is exceedingly small. We have spent two billion dollars on the greatest scientific gamble in history—and won.



SHANGRI-LA *looks like this. Not an idyllic pastoral valley but an ultra-modern power plant is revealed in this photograph released by the War Department. This is a general view of the Oak Ridge, Tenn. atomic power project, one of the hush-hush locations where this top secret research was carried on.*

But the greatest marvel is not the size of the enterprise, its secrecy, nor its cost, but the achievement of scientific brains in putting together infinitely complex pieces of knowledge held by many men in different fields of science into a workable plan. And hardly less marvellous has been the capacity of industry to design, and of labor to operate, the machines and methods to do things never done before so that the brain child of many minds came forth in physical shape and performed as it was supposed to do. Both science and industry worked under the direction of the United States Army, which achieved a unique success in managing so diverse a problem in the advancement of knowledge in an amazingly short time. It is doubtful if such another combination could be got together in the world. What has been done is the greatest achievement of organized science in history. It was done under high pressure and without failure.

We are now prepared to obliterate more rapidly and completely every

productive enterprise the Japanese have above ground in any city. We shall destroy their docks, their factories, and their communications. Let there be no mistake; we shall completely destroy Japan's power to make war.

It was to spare the Japanese people from utter destruction that the ultimatum of July 26 was issued at Potsdam. Their leaders promptly rejected that ultimatum. If they do not now accept our terms they may expect a rain of ruin from the air, the like of which has never been seen on this earth. Behind this air attack will follow sea and land forces in such numbers and power as they have not yet seen and with the fighting skill of which they are already well aware.

The Secretary of War, who has kept in personal touch with all phases of the project, will immediately make public a statement giving further details.

His statement will give facts concerning the sites at Oak Ridge near Knoxville, Tennessee, and at Richland near Pasco, Washington, and an installation near Santa Fe, New Mexico. Although the workers at the sites have been making materials to be used in producing the greatest destructive force in history they have not themselves been in danger beyond that of many other occupations, for the utmost care has been taken of their safety.

The fact that we can release atomic energy ushers in a new era in man's understanding of nature's forces. Atomic energy may in the future supplement the power that now comes from coal, oil, and falling water, but at present it cannot be produced on a basis to compete with them commercially. Before that comes there must be a long period of intensive research.

It has never been the habit of the scientists of this country or the policy of this Government to withhold from the world scientific knowledge. Normally, therefore, everything about the work with atomic energy would be made public.

But under present circumstances it is not intended to divulge the technical processes of production or all the military applications, pending further examination of possible methods of protecting us and the rest of the world from the danger of sudden destruction.

I shall recommend that the Congress of the United States consider promptly the establishment of an appropriate commission to control the production and use of atomic power within the United States. I shall give further consideration and make further recommendations to the Congress as to how atomic power can become a powerful and forceful influence towards the maintenance of world peace.

➤ ACRES *of diffusion apparatus were required to separate uranium's active isotope, number 235, from the 99 per cent of number 238 which makes up the usual uranium ore. This War Department photograph shows the extent of the plant required for such operations at Oak Ridge, Tenn.*

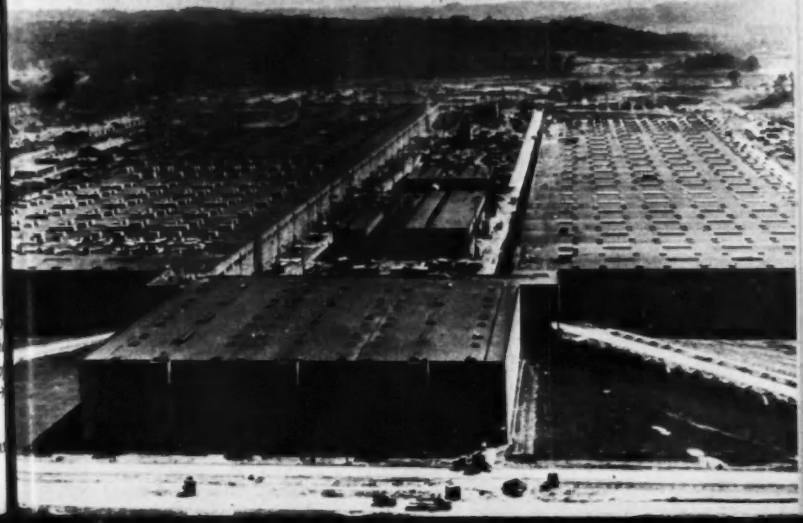
Self-Propagating Chain Reaction From Fission of Uranium Atom

Atomic Power

Information necessary to solve the problem of how to use atomic power was already in the hands of physicists and chemists in 1940. The following quotation from the Smyth Report describes the steps by which the knowledge then available was brought together and the problem stated. In the study of uranium fission, it was learned that U-238 the commonest isotope of uranium, which was not the material wanted for production of atomic energy, could be induced to capture neutrons and change into heavier elements. These new elements had been previously detected, it is true, by delicate radio-active techniques, but from the viewpoint of the chemist they were practically unknown. How they were virtually manufactured to order for atomic disintegration purposes is told in a later extract from the report.

The Need of a Chain Reaction

➤ OUR COMMON SOURCES of power, other than sunlight and water power, are chemical reactions—usually the combustion of coal or oil. They release energy as the result of rearrangements of the outer electronic structures of the atoms, the same kind of process that supplies energy to our bodies. Combustion is always self-propagating; thus lighting a fire with a match releases enough heat to ignite the neighboring fuel, which releases more heat which ignites more



fuel, and so on. In the nuclear reactions we have described this is not generally true; neither the energy released nor the new particles formed are sufficient to maintain the reaction. But we can imagine nuclear reactions emitting particles of the same sort that initiate them and in sufficient numbers to propagate the reaction in neighboring nuclei. Such a self-propagating reaction is called a "chain reaction" and such conditions must be achieved if the energy of the nuclear reactions with which we are concerned is to be put to large-scale use.

Period of Speculation

Although there were no atomic power plants built in the thirties, there were plenty of discoveries in nuclear physics and plenty of speculation. A theory was advanced by H. Bethe to explain the heat of the sun by a cycle of nuclear changes involving carbon, hydrogen, nitrogen, and oxygen, and leading eventually to the formation of helium.* This theory is now generally accepted. The discovery of a few (n,2n) nuclear reactions (i.e., neutron-produced and neutron-producing reactions) suggested that a self-multiplying chain reaction might be initiated under the right conditions. There was much talk of atomic power and some talk of atomic bombs. But the last great step in this preliminary period came after four years of stumbling. The effects of neutron bombardment of uranium, the most complex element known, had been studied by some of the ablest physicists. The results were striking but confusing. The story of their gradual interpretation is intricate and highly technical, a fascinating tale of theory and experiment. Passing by the earlier inadequate explanations, we shall go directly to the final explanation, which, as so often happens, is relatively simple.

Discovery of Uranium Fission

As has already been mentioned, the neutron proved to be the most effective particle for inducing nuclear changes. This was particularly true for the elements of highest atomic number and weight where the large nuclear charge exerts strong repulsive forces on deuteron or proton projectiles but not on uncharged neutrons. The results of the bombardment of uranium by neutrons had proved interesting and puzzling. First studied by Fermi and his colleagues in 1934, they were not properly interpreted until several years later.

On January 16, 1939 Niels Bohr of Copenhagen, Denmark, arrived in this country to spend several months in Princeton, N. J., and was particularly anxious to discuss some abstract problems with A. Einstein. (Four years later Bohr was to escape from Nazi-occupied Denmark in a small boat.) Just before Bohr left Denmark two of his colleagues, O. R. Frisch and L. Meitner (both refugees from Germany), had told him their guess that the absorption of a neutron by

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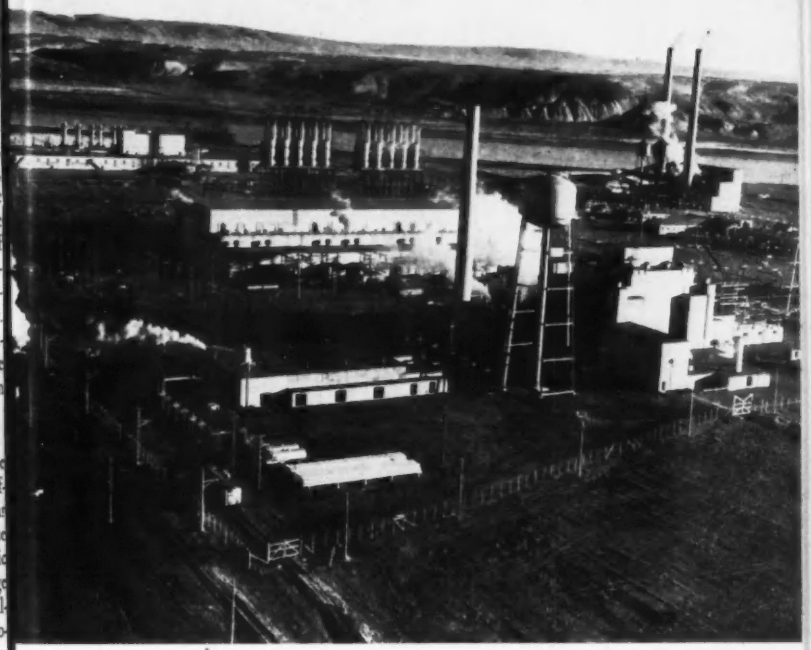
* The series of reactions postulated was

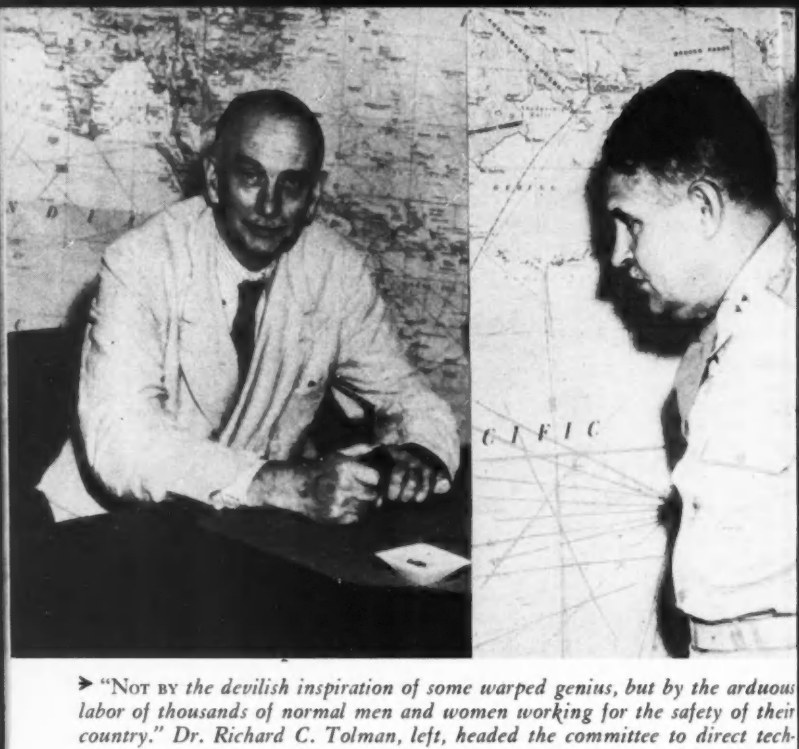
(1) ${}_6C^{12} + {}_1H^1 \rightarrow {}_7N^{13}$
(2) ${}_7N^{13} \rightarrow {}_6C^{13} + {}_1e^0$
(3) ${}_6C^{13} + {}_1H^1 \rightarrow {}_7N^{14}$
(4) ${}_7N^{14} + {}_1H^1 \rightarrow {}_8O^{15}$
(5) ${}_8O^{15} \rightarrow {}_7N^{15} + {}_1e^0$
(6) ${}_7N^{15} + {}_1H^1 \rightarrow {}_6C^{12} + {}_2He^4$

The net effect is the transformation of hydrogen into helium and positrons (designated as ${}_1e^0$) and the release of about thirty million electron volts energy.



▸ PLUTONIUM *by the pound. Here, by the pure cold water of the Columbia River, man set out to manufacture a new chemical element so deadly that no one could go near it. This War Department photograph shows the plant at Hanford, Washington, where all processes are handled through instruments by remote control.*

a uranium nucleus sometimes caused that nucleus to split into approximately equal parts with the release of enormous quantities of energy, a process that soon began to be called nuclear "fission." The occasion for this hypothesis was the important discovery of O. Hahn and F. Strassmann in Germany (published in *Naturwissenschaften* in early January 1939) which proved that an isotope of barium was produced by neutron bombardment of uranium. Immediately on arrival in the United States Bohr communicated this idea to his former student J. A. Wheeler and others at Princeton, and from them the news spread by word of mouth to neighboring physicists including E. Fermi at Columbia University. As a result of conversations between Fermi, J. R. Dunning, and G. B. Pegram, a search was undertaken at Columbia for the



➤ "Not by *the devilish inspiration of some warped genius, but by the arduous labor of thousands of normal men and women working for the safety of their country." Dr. Richard C. Tolman, left, headed the committee to direct technical development of nuclear energy along the paths of peace. Maj. Gen. L. R. Groves, right, in 1942 was placed in charge of all Army activities relating to the DSM project, the atomic bomb. By a classic of understatement, adopted for security reasons, DSM stands for Development of Substitute Materials.*

heavy pulses of ionization that would be expected from the flying fragments of the uranium nucleus. On January 26, 1939 there was a Conference on Theoretical Physics at Washington, D. C., sponsored jointly by the George Washington University and the Carnegie Institution of Washington. Fermi left New York to attend this meeting before the Columbia fission experiments had been tried. At the meeting Bohr and Fermi discussed the problem of fission, and in particular Fermi mentioned the possibility that neutrons might be emitted during the process. Although this was only a guess, its implication of the possibility of a chain reaction was obvious. A number of sensational articles were published in the press on this subject. Before the meeting in Washington was over, several other experiments to confirm fission had been initiated, and positive experimental confirmation was reported from four laboratories (Columbia University, Carnegie Institution of Washington, Johns Hop-

kins University, University of California) in the February 15, 1939 issue of the *Physical Review*. By this time Bohr had heard that similar experiments had been made in his laboratory in Copenhagen about January 15th. (Letter by Frisch to *Nature* dated January 16, 1939 and appearing in the February 18th issue). F. Joliot in Paris had also published his first results in the *Comptes Rendus* of January 30, 1939. From this time on there was a steady flow of papers on the subject of fission, so that by the time (December 6, 1939) Turner wrote a review article on the subject in the *Reviews of Modern Physics* nearly one hundred papers had appeared. Complete analysis and discussion of these papers have appeared in Turner's article and elsewhere.

General Discussion of Fission

Consider the suggestion of Frisch and Meitner in the light of the two general trends that had been discovered in nuclear structure:—first, that the proportion of neutrons goes up with atomic number; second, that the binding energy per particle is a maximum for the nuclei of intermediate atomic number. Suppose the U-238 nucleus is broken exactly in half; then, neglecting the mass of the incident neutron, we have two nuclei of atomic number 46 and mass number 119. But the heaviest stable isotope of palladium (Z = 46) has a mass number of only 110. Therefore to reach stability each of these imaginary new nuclei must eject nine neutrons, becoming $_{46}Pd^{110}$ nuclei; or four neutrons in each nucleus must convert themselves to protons by emitting electrons, thereby forming stable tin nuclei of mass number 119 and atomic number 50; or a combination of such ejections and conversions must occur to give some other pair of stable nuclei. Actually, as was suggested by Hahn and Strassmann's identification of barium (Z = 56, A = 135 to 140) as a product of fission, the split occurs in such a way as to produce two unequal parts of mass numbers about 140 and 90 with the emission of a few neutrons and subsequent radioactive decay by electron emission until stable nuclei are formed. Calculations from binding-energy data show that any such rearrangement gives an aggregate resulting mass considerably less than the initial mass of the uranium nucleus, and thus that a great deal of energy must be released.

Evidently, there were three major implications of the phenomenon of fission: the release of energy, the production of radioactive atomic species and the possibility of a neutron chain reaction. The energy release might reveal itself in kinetic energy of the fission fragments and in the subsequent radioactive disintegration of the products. The possibility of a neutron chain reaction depended on whether neutrons were in fact emitted—a possibility which required investigation.

These were the problems suggested by the discovery of fission, the kind of problem reported in the journals in 1939 and 1940 and since then investigated largely in secret. The study of the fission process itself, including production of neutrons and fast fragments, has been largely carried out by physicists using counters, cloud chambers, etc. The study and identification of the fission products has

been carried out largely by chemists, who have had to perform chemical separations rapidly even with submicroscopic quantities of material and to make repeated determinations of the half-lives of unstable isotopes. We shall summarize the state of knowledge as of June 1940. By that time the principal facts about fission had been discovered and revealed to the scientific world. A chain reaction had not been obtained, but its possibility—at least in principle—was clear and several paths that might lead to it had been suggested.

State of Knowledge, June 1940

All the following information was generally known in June 1940, both here and abroad:

(1) That three elements — uranium, thorium, and protoactinium—when bombarded by neutrons sometimes split into approximately equal fragments, and that these fragments were isotopes of elements in the middle of the periodic table, ranging from selenium ($Z = 34$) to lanthanum ($Z = 57$).

(2) That most of these fission fragments were unstable, decaying radioactively by successive emission of beta particles through a series of elements to various stable forms.

(3) That these fission fragments had very great kinetic energy.

(4) That fission of thorium and protoactinium was caused only by fast neutrons (velocities of the order of thousands of miles per second).

(5) That fission in uranium could be produced by fast or slow (so-called thermal-velocity) neutrons; specifically, that thermal neutrons caused fission in one isotope, U-235, but not in the other, U-238, and that fast neutrons had a lower probability of causing fission in U-235 than thermal neutrons.

(6) That at certain neutron speeds there was a large capture cross section in U-238 producing U-239 but not fission.

(7) That the energy released per fission of a uranium nucleus was approximately 200 million electron volts.

(8) That high speed neutrons were emitted in the process of fission.

(9) That the average number of neutrons released per fission was somewhere between one and three.

(10) That high-speed neutrons could lose energy by inelastic collision with uranium nuclei without any nuclear reaction taking place.

(11) That most of this information was consistent with the semi-empirical theory of nuclear structure worked out by Bohr and Wheeler and others; this suggested that predictions based on this theory had a fair chance of success.

Suggestion of Plutonium Fission

It was realized that radiative capture of neutrons by U-238 would probably lead by two successive beta-ray emissions to the formation of a nucleus for which $Z = 94$ and $A = 239$. Consideration of the Bohr-Wheeler theory of fission and of certain empirical relations among the nuclei by L. A. Turner and others suggested that this nucleus would be a fairly stable alpha emitter and would probably undergo fission when bombarded by thermal neutrons. Later the importance of such thermal fission to the maintenance of the chain reaction was

foreshadowed in private correspondence and discussion. In terms of our present knowledge and notation the particular reaction suggested is as follows:

$$_{92}U^{238} + {}_{0}n^{1} \rightarrow {}_{92}U^{239} \rightarrow {}_{93}Np^{239} + {}_{-1}e^{0}$$
$$_{93}Np^{239} \rightarrow {}_{94}Pu^{239} + {}_{-1}e^{0}$$

where Np and Pu are the chemical symbols now used for the two new elements, neptunium and plutonium; $_{0}n^{1}$ represents the neutron, and $_{-1}e^{0}$ represents an ordinary (negative) electron. Plutonium 239 is the nucleus rightly guessed to be fissionable by thermal neutrons. It will be discussed fully in later chapters.

General State of Nuclear Physics

By 1940 nuclear reactions had been intensively studied for over ten years. Several books and review articles on nuclear physics had been published. New techniques had been developed for producing and controlling nuclear projectiles, for studying artificial radioactivity, and for separating submicroscopic quantities of chemical elements produced by nuclear reactions. Isotope masses had been measured accurately. Neutron-capture cross sections had been measured. Methods of slowing down neutrons had been developed. Physiological effects of neutrons had been observed; they had even been tried in the treatment of cancer. All such information was generally available; but it was very incomplete. There were many gaps and many inaccuracies. The techniques were difficult and the quantities of materials available were often submicroscopic. Although the fundamental principles were clear, the theory was full of unverified assumptions and calculations were hard to make. Predictions made in 1940 by different physicists of equally high ability were often at variance. The subject was in all-too-many respects an art, rather than a science.

Choice of Element 94

▸ Since the first report of the National Academy of Sciences Committee on Atomic Fission, an extremely important new possibility has been opened for the exploitation of the chain reaction with unseparated isotopes of uranium. Experiments in the Radiation Laboratory of the University of California have indicated (a) that element 94 is formed as a result of capture of a neutron by uranium 238 followed by two successive beta-transformations, and furthermore (b) that this transuranic element undergoes slow neutron fission and therefore presumably behaves like uranium 235.

It appears accordingly that, if a chain reaction with unseparated isotopes is achieved, it may be allowed to proceed violently for a period of time for the express purpose of manufacturing element 94 in substantial amounts. This material could be extracted by ordinary chemistry and would presumably be the equivalent of uranium 235 for chain reaction purposes.

—*Report of E. O. Lawrence to the National Academy Committee, 1941.*

Fission Produces New Neutrons Which Start Chain Reaction

The Production Problem

In 1940 it was possible to state the theoretical conditions under which one explosion of atomic energy might set off another. No one knew whether these conditions would be realized, nor what the result would be. How such problems were worked out is told in this chapter of the Smyth Report.

➤ FROM THE TIME of the first discovery of the large amounts of energy released in nuclear reactions to the time of the discovery of uranium fission, the idea of atomic power or even atomic bombs was discussed off and on in scientific circles. The discovery of fission made this talk seem much less speculative, but realization of atomic power still seemed in the distant future and there was an instinctive feeling among many scientists that it might not, in fact, ever be realized. During 1939 and 1940 many public statements, some of them by responsible scientists, called attention to the enormous energy available in uranium for explosives and for controlled power, so that U-235 became a familiar by-word indicating great things to come. The possible military importance of uranium fission was called to the attention of the government, and in a conference with representatives of the Navy Department in March 1939 Fermi suggested the possibility of achieving a controllable reaction using slow neutrons or a reaction of an explosive character using fast neutrons. He pointed out, however, that the data then available might be insufficient for accurate predictions.

By the summer of 1940 it was possible to formulate the problem fairly clearly, although it was still far from possible to answer the various questions involved or even to decide whether a chain reaction ever could be obtained. In this chapter we shall give a statement of the problem in its entirety. For purposes of clarification we may make use of some knowledge which actually was not acquired until a later date.

The Chain-Reaction Problem

The principle of operation of an atomic bomb or power plant utilizing uranium fission is simple enough. If one neutron causes a fission that produces more than one new neutron, the number of fissions may increase tremendously with the release of enormous amounts of energy. It is a question of probabilities. Neutrons produced in the fission process may escape entirely from the uranium, may be captured by uranium in a process not resulting in fission, or may be captured by an impurity. Thus the question of whether a chain reaction does or does not go depends on the result of a competition among four processes:

(1) escape,
(2) non-fission capture by uranium,
(3) non-fission capture by impurities,
(4) fission capture.

If the loss of neutrons by the first three processes is less than the surplus produced by the fourth, the chain reaction occurs; otherwise it does not. Evidently any one of the first three processes may have such a high probability in a given arrangement that the extra neutrons created by fission will be insufficient to keep the reaction going. For example, should it turn out that process (2)—non-fission capture by uranium—has a much higher probability than fission capture, there would presumably be no possibility of achieving a chain reaction.

An additional complication is that natural uranium contains three isotopes: U-234, U-235, and U-238, present to the extent of approximately 0.006, 0.7, and 99.3 per cent, respectively. We have already seen that the probabilities of processes (2) and (4) are different for different isotopes. We have also seen that the probabilities are different for neutrons of different energies.

We shall now consider the limitations imposed by the first three processes and how their effects can be minimized.

Critical Size

The relative number of neutrons which escape from a quantity of uranium can be minimized by changing the size and shape. In a sphere any surface effect is proportional to the square of the radius, and any volume effect is proportional to the cube of the radius. Now the escape of neutrons from a quantity of uranium is a surface effect depending on the area of the surface, but fission capture occurs throughout the material and is therefore a volume effect. Consequently the greater the amount of uranium, the less probable it is that neutron escape will predominate over fission capture and prevent a chain reaction. Loss ot neutrons by non-fission capture is a volume effect like neutron production by fission capture, so that increase in size makes no change in its relative importance.

The critical size of a device containing uranium is defined as the size for which the production of free neutrons by fission is just equal to their loss by escape and by non-fission capture. In other words, if the size is smaller than critical, then—by definition—no chain reaction will sustain itself. In principle it was possible in 1940 to calculate the critical size, but in practice the uncertainty of the constants involved was so great that the various estimates differed widely. It seemed not improbable that the critical size might be too large for practical purposes. Even now estimates for untried arrangements vary somewhat from time to time as new information becomes available.

Use of a Moderator

In Chapter I* we said that thermal neutrons have the highest probability of producing fission of U-235 but we also said that the neutrons emitted in the process of fission had high speeds. Evidently it was an oversimplification to say that the chain reaction might maintain itself if more neutrons were created by fission than were absorbed. For the probability both of fission capture and of non-fission capture depends on the speed of the neutrons. Unfortunately, the speed at which non-fission capture is most probable is intermediate between the

* See page 10.

average speed of neutrons emitted in the fission process and the speed at which fission capture is most probable.

For some years before the discovery of fission, the customary way of slowing down neutrons was to cause them to pass through material of low atomic weight, such as hydrogenous material. It was E. Fermi and L. Szilard who proposed the use of graphite as a moderator for a chain reaction. The process of slowing down or moderation is simply one of elastic collisions between high-speed particles and particles practically at rest. The more nearly identical the masses of neutron and struck particle the greater the loss of kinetic energy by the neutron. Therefore the light elements are most effective as "moderators," i.e., slowing down agents, for neutrons.

It occurred to a number of physicists that it might be possible to mix uranium with a moderator in such a way that the high-speed fission neutrons, after being ejected from uranium and before re-encountering uranium nuclei, would have their speeds reduced below the speeds for which non-fission capture is highly probable. Evidently the characteristics of a good moderator are that it should be of low atomic weight and that it should have little or no tendency to absorb neutrons. Lithium and boron are excluded on the latter count. Helium is difficult to use because it is a gas and forms no compounds. The choice of moderator therefore lay between hydrogen, deuterium, beryllium, and carbon. Even now no one of these substances can be excluded from the list of practical possibilities.

Use of a Lattice

The general scheme of using a moderator mixed with the uranium was pretty obvious. A specific manner of using a moderator was first suggested in this country, so far as we can discover, by Fermi and Szilard. The idea was to use lumps of uranium of considerable size imbedded in a matrix of moderator material. Such a lattice can be shown to have real advantages over a homogeneous mixture. As the constants were more accurately determined, it became possible to calculate theoretically the type of lattice that would be most effective.

Isotope Separation

In Chapter I* it was stated that for neutrons of certain intermediate speeds (corresponding to energies of a few electron volts) U-238 has a large capture cross section for the production of U-239 but not for fission. There is also a considerable probability of inelastic (i.e., non-capture-producing) collisions between high-speed neutrons and U-238 nuclei. Thus the presence of the U-238 tends both to reduce the speed of the fast neutrons and to effect the capture of those of moderate speed. Although there may be some non-fission capture by U-235, it is evident that if we can separate the U-235 from the U-238 and discard the U-238, we can reduce non-fission capture and can thus promote the chain reaction. In fact, the probability of fission of U-235 by high-speed neutrons may be great enough to make the use of a moderator unnecessary once the U-238 has been removed. Unfortunate

* See page 10.

ly, U-235 is present in natural uranium only to the extent of about one part in 140. Also, the relatively small difference in mass between the two isotopes makes separation difficult. In fact, in 1940 no large-scale separation of isotopes had ever been achieved except for hydrogen, whose two isotopes differ in mass by a factor of two. Nevertheless, the possibility of separating U-235 was recognized early as being of the greatest importance, and such separation has, in fact, been one of the two major lines of Project effort during the past five years.

Purification of Materials

It has been stated above that the cross section for capture of neutrons varies greatly among different materials. In some it is very high compared to the maximum fission cross section of uranium. If, then, we are to hope to achieve a chain reaction, we must reduce effect (3)—non-fission capture by impurities—to the point where it is not serious. This means very careful purification of the uranium metal and very careful purification of the moderator. Calculations show that the maximum permissible concentrations of many impurity elements are a few parts per million—in either the uranium or the moderator. When it is recalled that up to 1940 the total amount of uranium metal produced in this country was not more than a few grams (and even this was of doubtful purity), that the total amount of metallic beryllium produced in this country was not more than a few pounds, that the total amount of concentrated deuterium produced was not more than a few pounds, and that carbon had never been produced in quantity with anything like the purity required of a moderator, it is clear that the problem of producing and purifying materials was a major one.

Control of the Chain Reaction

The problems that have been discussed so far have to do merely with the realization of the chain reaction. If such a reaction is going to be of use, we must be able to control it. The problem of control is different depending on whether we are interested in steady production of power or in an explosion. In general, the steady production of atomic power requires a slow-neutron-induced fission chain reaction occurring in a mixture or lattice of uranium and moderator, while an atomic bomb requires a fast-neutron-induced fission chain reaction in U-235 or Pu-239, although both slow- and fast-neutron fission may contribute in each case. It seemed likely, even in 1940, that by using neutron absorbers a power chain reaction could be controlled. It was also considered likely, though not certain, that such a chain reaction would be self-limiting by virtue of the lower probability of fission-producing capture when a higher temperature was reached. Nevertheless, there was a possibility that a chain-reacting system might get out of control, and it therefore seemed necessary to perform the chain-reaction experiment in an uninhabited location.

Practical Application

Up to this point we have been discussing how to produce and control a nuclear chain reaction but not how to make use of it. The technological gap between producing a controlled chain reaction and using it as a large-scale power source or an explosive is

comparable to the gap between the discovery of fire and the manufacture of a steam locomotive.

Although production of power has never been the principal object of this project, enough attention has been given to the matter to reveal the major difficulty: the attainment of high-temperature operation. An effective heat engine must not only develop heat but must develop heat at a high temperature. To run a chain-reacting system at a high temperature and to convert the heat generated to useful work is very much more difficult than to run a chain-reacting system at a low temperature.

Of course, the proof that a chain reaction is possible does not itself insure that nuclear energy can be effective in a bomb. To have an effective explosion it is necessary that the chain reaction build up extremely rapidly; otherwise only a small amount of the nuclear energy will be utilized before the bomb flies apart and the reaction stops. It is also necessary that no premature explosion occur. This entire "detonation" problem was and still remains one of the most difficult problems in designing a high-efficiency atomic bomb.

Possibility of Using Plutonium

So far, all our discussion has been primarily concerned with the use of uranium itself. We have already mentioned the suggestion that the element of atomic number 94 and mass 239, commonly referred to as plutonium, might be very effective. Actually, we now believe it to be of value comparable to pure U-235. We have mentioned the difficulty of separating U-235 from the more abundant isotope U-238. These two isotopes are, of course, chemically identical. But plutonium, although produced from U-238, is a different chemical element. Therefore, if a process could be worked out for converting some of the U-238 to plutonium, a *chemical* separation of the plutonium from uranium might prove more practicable than the *isotopic* separation of U-235 from U-238.

Suppose that we have set up a controllable chain reaction in a lattice of natural uranium and a moderator —say carbon, in the form of graphite. Then as the chain reaction proceeds, neutrons are emitted in the process of fission of the U-235 and many of these neutrons are absorbed by U-238. This produces U-239, each atom of which then emits a beta particle, becoming neptunium ($_{93}Np^{239}$). Neptunium, in turn, emits another beta particle, becoming plutonium ($_{94}Pu^{239}$), which emits an alpha particle, decaying again to U-235, but so slowly that in effect it is a stable element. If, after the reaction has been allowed to proceed for a considerable time, the mixture of metals is removed, it may be possible to extract the plutonium by chemical methods and purify it for use in a subsequent fission chain reaction of an explosive nature.

Combined Effects

Three ways of increasing the likelihood of a chain reaction have been mentioned: use of a moderator; attainment of high purity of materials; use of special material, either U-235 or Pu. The three procedures are not mutually exclusive, and many schemes have been proposed for using small

amounts of separated U-235 or Pu-239 in a lattice composed primarily of ordinary uranium or uranium oxide and of a moderator or two different moderators. Such proposed arrangements are usually called "enriched piles."

Use of Other Material

All our previous discussion has centered on the direct or indirect use of uranium, but it was known that both thorium and protoactinium also underwent fission when bombarded by high-speed neutrons. The great advantage of uranium, at least for preliminary work, was its susceptibility to slow neutrons. There was not very much consideration given to the other two substances. Protoactinium can be eliminated because of its scarcity in nature. Thorium is relatively plentiful but has no apparent advantage over uranium.

It is not to be forgotten that theoretically many nuclear reactions might be used to release energy. At present we see no way of initiating or controlling reactions other than those involving fission, but some such synthesis as has already been mentioned as a source of solar energy may eventually be produced in the laboratory.

Amounts of Materials

Obviously it was impossible in the summer of 1940 to make more than guesses as to what amounts of materials would be needed to produce:

(1) a chain reaction with use of a moderator;

(2) a chain-reaction bomb in pure, or at least enriched, U-235 or plutonium.

A figure of one to one hundred kilograms of U-235 was commonly given at this time for the critical size of a bomb. This would, of course, have to be separated from at least 140 times as much natural uranium. For a slow-neutron chain reaction using a moderator and unseparated uranium it was almost certain that tons of metal and of moderator would be required.

Materials and Costs

How to provide materials in quantities never before dreamed of, in grades of purity never before attempted on such a scale, for processes for which there was no precedent, was only one of the problems confronting the research group. How they surveyed this field is told in the following extract.

➤ ESTIMATES of the composition of the earth's crust show uranium and thorium both present in considerable quantities (about 4 parts per million of uranium and 12 parts per million of thorium in the earth's crust). Deposits of uranium ore are known to exist in Colorado, in the Great Bear Lake region of northern Canada, in Joachimstal in Czechoslovakia, and in the Belgian Congo. Many other deposits of uranium ore are known, but their extent is in many cases unexplored. Uranium is always found with radium although in much larger quantity. Both are often found with vanadium ores. Small quantities of uranium oxide have been used for many years in the ceramics industry.

Thorium is also rather widely distributed, occurring as thorium oxide

in fairly high concentration in monazite sands found to some extent in this country but particularly in Brazil and in British India.

Early rough estimates, which are probably optimistic, were that the nuclear energy available in known deposits of uranium was adequate to supply the total power needs of this country for 200 years (assuming utilization of U-238 as well as U-235).

As has already been mentioned, little or no uranium metal had been produced up to 1940 and information was so scant that even the melting point was not known. (For example, the *Handbook of Physics and Chemistry* for 1943-1944 says only that the melting point is below 1850°C whereas we now know it to be in the neighborhood of 1150°.) Evidently, as far as uranium was concerned, there was no insurmountable difficulty as regards obtaining raw materials or producing the metal, but there were very grave questions as to how long it would take and how much it would cost to produce the necessary quantities of pure metal.

Of the materials mentioned above as being suitable for moderators, deuterium had the most obvious advantages. It is present in ordinary hydrogen to the extent of about one part in 5000. By 1940 a number of different methods for separating it from hydrogen had been developed, and a few liters had been produced in this country for experimental purposes. The only large-scale production had been in a Norwegian plant, from which several hundred liters of heavy water (D_2O, deuterium oxide) had come. As in the case of uranium, the problem was one of cost and time.

Beryllium in the form of beryllium silicates is widely found but only in small quantities of ore. Its use as an alloying agent has become general in the last few years; for such use, however, it is not necessary to produce the beryllium in metallic form. In 1940 only 700 pounds of the metal were produced in this country.

As far as carbon was concerned, the situation was obviously quite different. There were many hundreds of tons of graphite produced every year in this country. This was one of the reasons why graphite looked very desirable as a moderator. The difficulties lay in obtaining sufficient quantities of graphite of the required purity, particularly in view of the expanding needs of war industry.

Time and Cost Estimates

Requirements of time and money depended not only on many unknown scientific and technological factors but also on policy decisions. Evidently years of time and millions of dollars might be required to achieve the ultimate objective. About all that was attempted at this time was making estimates as to how long it would take and how much it would cost to clarify the scientific and technological prospects. It looked as if it would not be a very great undertaking to carry along the development of the thermal-neutron chain reaction in a graphite-uranium lattice to the point of finding out whether the reaction would in fact go. Estimates made at the time were that approximately a year and $100,000 would be required to get an answer. These estimates applied to a chain-reacting system of very low power without a cooling system or any means for using the energy released.

Method of Approach

There were two ways of attacking the problem. One was to conduct elaborate series of accurate physical measurements on absorption cross sections of various materials for various neutron-induced processes and various neutron energies. Once such data were available, calculations as to what might be done in the way of a chain reaction could be made with fair accuracy. The other approach was the purely empirical one of mixing uranium or uranium compounds in various ways with various moderators and observing what happened. Similar extremes of method were possible in the case of the isotope-separation problem. Actually an intermediate or compromise approach was adopted in both cases.

Power vs. Bomb

The expected military advantages of uranium bombs were far more spectacular than those of a uranium power plant. It was conceivable that a few uranium bombs might be decisive in winning the war for the side first putting them into use. Such thoughts were very much in the minds of those working in this field, but the attainment of a slow-neutron chain reaction seemed a necessary preliminary step in the development of our knowledge and became the first objective of the group interested in the problem. This also seemed an important step in convincing military authorities and the more skeptical scientists that the whole notion was not a pipe dream. Partly for these reasons and partly because of the extreme secrecy imposed about this time, the idea of an atomic bomb does not appear much in the records between the summer of 1940 and the fall of 1941.

Military Usefulness

If all the atoms in a kilogram of U-235 undergo fission, the energy released is equivalent to the energy released in the explosion of about 20,000 short tons of TNT. If the critical size of a bomb turns out to be practical —say, in the range of one to one hundred kilograms—and all the other problems can be solved, there remain two questions. First, how large a percentage of the fissionable nuclei can be made to undergo fission before the reaction stops; i.e., what is the efficiency of the explosion? Second, what is the effect of so concentrated a release of energy? Even if only 1 percent of the theoretically available energy is released, the explosion will still be of a totally different order of magnitude from that produced by any previously known type of bomb. The value of such a bomb was thus a question for military experts to consider very carefully.

Summary

It has been established (1) that uranium fission did occur with release of great amounts of energy; and (2) that in the process extra neutrons were set free which might start a chain reaction. It was not contrary to any known principle that such a reaction should take place and that it should have very important military application as a bomb. However, the idea was revolutionary and therefore suspect; it was certain that many technical operations of great difficulty would have to be worked out before such a bomb could be produced. Probably the only materials satisfactory for a bomb were either U-235, which

would have to be separated from the 140-times more abundant isotope U-238, or Pu-239, an isotope of the hitherto unknown element plutonium, which would have to be generated by a controlled chain-reacting process itself hitherto unknown. To achieve such a controlled chain reaction it was clear that uranium metal and heavy water or beryllium or carbon might have to be produced in great quantity with high purity. Once bomb material was produced a process would have to be developed for using it safely and effectively. In some of the processes, health hazards of a new kind would be encountered.

Policy Problem

By the summer of 1940 the National Defense Research Committee had been formed and was asking many of the scientists in the country to work on various urgent military problems. Scientific personnel was limited (although this was not fully realized at the time). It was, therefore, really difficult to decide at what rate work should be carried forward on an atomic bomb. The decision had to be reviewed at frequent intervals during the subsequent four years.

Would the Chain Reaction Go Under Any Circumstances?

How To Split an Atom

Three primary questions needing to be solved before the use of atomic power could be considered were: (1) Could any circumstances be found under which the chain reaction would go? (2) Could the isotope U-235 be separated on a large scale? (3) Could moderator and other materials be obtained in sufficient purity and quantity? Experiments designed to answer these questions were undertaken in 1940-41. This quotation from the Smyth Report tells of their success.

▶ In June 1940, nearly all work on the chain reaction was concentrated at Columbia under the general leadership of Pegram, with Fermi and Szilard in immediate charge. It had been concluded that the most-easily produced chain reaction was probably that depending on thermal neutron fission in a heterogeneous mixture of graphite and uranium. In the spring of 1940 Fermi, Szilard and H. L. Anderson had improved the accuracy of measurements of the capture cross section of carbon for neutrons, of the resonance (intermediate-speed) absorption of neutrons by U-238, and of the slowing down of neutrons in carbon.

Pegram, in a memorandum to Briggs on August 14, 1940, wrote, "It is not very easy to measure these quantities with accuracy without the use of large quantities of material. The net results of these experiments in the spring of 1940 were that the possibility of the chain reaction was not definitely proven, while it was still further from being definitely disproven. On the whole, the indications were more favorable than any conclusions that could fairly have been claimed from previous results."

At a meeting on June 15th these results were discussed and it was recommended that (A) further meas-

urements be made on nuclear constants, and (B) experiments be made on lattices of uranium and carbon containing amounts of uranium from one fifth to one quarter the estimated critical amounts.

Progress up to Feb. 15, 1941

Pegram's report of February 15, 1941 shows that most of the work done up to that time was done on (A), while (B), the so-called intermediate experiment, was delayed by lack of materials.

Paraphrasing Pegram's report, the main progress was as follows:

(a) *The slowing down of neutrons* in graphite was investigated by studying the intensity of activation of various detectors (rhodium, indium, iodine) placed at various positions inside a rectangular graphite column of dimensions 3 x 3 x 8 feet when a source of neutrons was placed therein. By suitable choice of cadmium screens the effects of resonance and thermal neutrons were investigated separately.* A mathematical analysis, based on diffusion theory, of the experimental data made it possible to predict the results to be expected in various other arrangements. These results, coupled with theoretical studies of the diffusion of thermal neutrons, laid a basis for future calculations of the number of thermal and resonance neutrons to be found at any point in a graphite mass of given shape when a given neutron source is placed at a specified position within or near the graphite.

(b) *The number of neutrons emitted in fission.* The experiments on slowing down neutrons showed that high-energy (high-speed) neutrons such as those from fission were practically all reduced to thermal energies (low speeds) after passing through 40 cm or more of graphite. A piece of uranium placed in a region where thermal neutrons are present absorbs the thermal neutrons and—as fission occurs—re-emits fast neutrons, which are easily distinguished from the thermal neutrons. By a series of measurements with and without uranium present and with various detectors and absorbers, it is possible to get a value for the constant η, the number of neutrons emitted per thermal neutron absorbed by uranium. This is not the number of neutrons emitted per fission, but is somewhat smaller than that number since not every absorption causes fission.

(c) *Lattice theory.* Extensive calculations were made on the probable number of neutrons escaping from lattices of various designs and sizes. This was fundamental for the so-called intermediate experiment, mentioned above as item (B).

Initiation of New Programs

Early in 1941 interest in the general chain-reaction problem by individuals at Princeton, Chicago, and California led to the approval of cer-

*The presence of neutrons can be detected by ionization chambers or counters or by the artificial radioactivity induced in various metal foils. The response of each of these detectors depends on the particular characteristics of the detector and on the speed of the neutrons (e.g., neutrons of about 1.5 volts energy are particularly effective in activating indium). Furthermore, certain materials have very large absorption cross sections for neutrons of particular ranges of speed (e.g., cadmium for thermal neutrons). Thus measurements with different detectors with or without various absorbers give some indication of both the number of neutrons present and their energy distribution. However, the state of the art of such measurements is rather crude.

tain projects at those institutions. Thereafter the work of these groups was coordinated with the work at Columbia, forming parts of a single large program.

Work on Resonance Absorption*

In Chapter II† it is stated that there were advantages in a lattice structure or "pile" with uranium concentrated in lumps regularly distributed in a matrix of moderator. This was the system on which the Columbia group was working. As is so often the case, the fundamental idea is a simple one. If the uranium and the moderator are mixed homogeneously, the neutrons on the average will lose energy in small steps between passages through the uranium so that in the course of their reduction to thermal velocity the chance of their passing through uranium at any given velocity, e.g., at a velocity corresponding to resonance absorption, is great. But, if the uranium is in large lumps spaced at large intervals in the moderator, the amounts of energy lost by neutrons between passages from one lump of uranium to another will be large and the chance of their reaching a uranium lump with energy just equal to the energy of resonance absorption is relatively small. Thus the chance of absorption by U-238 to produce U-239, compared to the chance of absorption as thermal neutrons to cause fission, may be reduced sufficiently to allow a chain reaction to take place. If one knew the exact values of the cross sections of each uranium isotope for each type of absorption and every range of neutron speed, and had similar knowledge for the moderator, one could calculate the "optimum lattice," i.e., the best size, shape and spacing for the lumps of uranium in the matrix of moderator. Since such data were only partially known, a direct experimental approach appeared to be in order. Consequently it was proposed that the absorption of neutrons by uranium should be measured under conditions similar to those expected in a chain-reacting pile employing graphite as moderator.

Experiments of this type were initiated at Columbia, and were continued at Princeton in February 1941. Essentially the experiment consisted of studying the absorption of neutrons in the energy range extending from a few thousand electron volts down to a fraction of an electron volt (thermal energies), the absorption taking place in different layers of uranium or uranium oxide spheres embedded in a pile of graphite.

In these experiments, a source of neutrons was provided by a beam of protons (accelerated by a cyclotron) impinging in a beryllium target. (The resulting yield of neutrons was equivalent to the yield from a radium-beryllium source of about 3500 curies strength.) The neutrons thus produced had a wide, continuous, velocity distribution. They proceeded from this source into a large block of gra

* The term "resonance absorption" is used to describe the very strong absorption of neutrons by U-238 when the neutron energies are in certain definite proportions of the energy region from 0 to 1000 electron volts. Such resonance absorption demonstrates the existence of nuclear energy levels at corresponding energies. On some occasions the term resonance absorption is used to refer to the whole energy region in the neighborhood of such levels.

† See page 14.

phite. By placing the various uranium or uranium-oxide spheres inside the graphite block at various positions representing increasing distances from the source, absorption of neutrons of decreasing average speeds down to thermal speeds was studied. It was found that the total absorption of neutrons by such spheres could be expressed in terms of a "surface" effect and a "mass" effect.

These experiments, involving a variety of sphere sizes, densities, and positions were continued until the spring of 1942, when most of the group was moved to Chicago. Similar experiments performed at a later date at the University of Indiana by A. C. G. Mitchell and his co-workers have verified and in some cases corrected the Princeton data, but the Princeton data were sufficiently accurate by the summer of 1941 to be used in planning the intermediate-pile experiments and the subsequent experiments on operating piles.

The experimental work on resonance absorption at Princeton was done by R. R. Wilson, E. C. Creutz, and their collaborators, under the general leadership of H. D. Smyth; they benefited from the constant help of Wigner and Wheeler and frequent conferences with the Columbia group.

First Intermediate Experiments

About July 1941 the first lattice structure of graphite and uranium was set up at Columbia. It was a graphite cube about 8 feet on an edge, and contained about 7 tons of uranium oxide in iron containers distributed at equal intervals throughout the graphite. A preliminary set of measurements was made on this structure in August 1941. Similar structures of somewhat larger size were set up and investigated during September and October, and the so-called exponential method (described below) of determining the multiplication factor was developed and first applied. This work was done by Fermi and his assistants, H. L. Anderson, B. Feld, G. Weil, and W. H. Zinn.

The multiplication-factor experiment is rather similar to that already outlined for the determination of η, the number of neutrons produced per thermal neutron absorbed. A radium-beryllium neutron source is placed near the bottom of the lattice structure and the number of neutrons is measured at various points throughout the lattice. These numbers are then compared with the corresponding numbers determined when no uranium is present in the graphite mass. Evidently the absorption of neutrons by U-238 to produce U-239 tends to reduce the number of neutrons, while the fissions tend to increase the number. The question is: Which predominates? or, more precisely, does the fission production of neutrons predominate over all neutron-removal processes other than escape? Interpretation of the experimental data on this crucial question involves many corrections, calculations, and approximations, but all reduce in the end to a single number, the multiplication factor k.

The Multiplication Factor k

The whole success or failure of the uranium project depended on the multiplication factor k, sometimes called the reproduction factor. If k could be made greater than one in a

practical system, the project would succeed; if not, the chain reaction would never be more than a dream. This is clear from the following discussion, which applies to any system containing fissionable material. Suppose that there is a certain number of free neutrons present in the system at a given time. Some of these neutrons will themselves initiate fissions and will thus directly produce new neutrons. The multiplication factor k is the ratio of the number of these new neutrons to the number of free neutrons originally present. Thus, if in a given pile comprising uranium, carbon, impurities, containers, etc., 100 neutrons are produced by fission, some will escape, some will be absorbed in the uranium without causing fission, some will be absorbed in the carbon, in the containers or in impurities, and some will cause fission, thereby producing more neutrons. If the fissions are sufficiently numerous and sufficiently effective individually, more than 100 new neutrons will be produced and the system is chain reacting. If the number of new neutrons is 105, $k = 1.05$. But if the number of new neutrons per 100 initial ones is 99, $k = .99$ and no chain reaction can maintain itself.

Recognizing that the intermediate or "exponential" experiment described above was too small to be chain reacting, we see that it was a matter of great interest whether any larger pile of the same lattice structure would be chain reacting. This could be determined by calculating what the value of k would be for an infinitely large lattice of this same type. In other words, the problem was to calculate what the value of k would be if no neutrons leaked away through the sides of the pile. Actually it is found that, once a chain-reacting system is well above the critical size—say two or three times as great—and is surrounded by what is called a reflector, the effective value of k differs very little from that for infinite size provided that k is near 1.00. Consequently, it has become customary to characterize the chain-reaction potentialities of different mixtures of metal and moderator by the value of k_∞ the multiplication constant obtained by assuming infinite size of pile.

The value of k_∞ as reported by Fermi to the Uranium Section in the fall of 1941 was about 0.87. This was based on results from the second Columbia intermediate experiment. All agreed that the multiplication factor could be increased by greater purity of materials, different lattice arrangements, etc. None could say with certainty that it could be made greater than one.

Theoretical Work

Both the intermediate experiments at Columbia and the continued resonance-absorption work at Princeton required skilful theoretical interpretation. Fermi worked out the theory of the "exponential" pile and Wigner the theory of resonance absorption; both these men were constantly conferring and contributing to many problems. Wheeler of Princeton, Breit of Wisconsin, and Eckart of Chicago —to mention only a few—also made contributions to general pile theory and related topics. Altogether one can say that by the end of 1941 the general theory of the chain reaction for slow neutrons was almost completely understood. It was the nu-

merical constants and technological possibilities that were still uncertain.

On the theory of a fast neutron reaction in U-235 a good deal of progress had also been made. In particular, new estimates of the critical size were made, and it was predicted that possibly 10 per cent of the total energy might be released explosively. On this basis one kilogram of U-235 would be equivalent to 2000 tons of TNT. The conclusions are reviewed below in connection with the National Academy Report. It is to be remembered that there are two factors involved: (1) how large a fraction of the available fission energy will be released before the reaction stops; (2) how destructive such a highly concentrated explosion will be.

Experiments on Beryllium

▶ AT ABOUT the same time that the work on resonance absorption was started at Princeton, S. K. Allison, at the suggestion of A. H. Compton, began work at Chicago under a contract running from January 1, 1941 to August 1, 1941. The stated objectives of the work were to investigate (a) the increase in neutron production when the pile is enclosed in a beryllium envelope or "reflector," and (b) the cross sections of beryllium. A new contract was authorized on July 18, 1941 to run to June 30, 1942. This stated the somewhat broader objective of investigating uranium-beryllium-carbon systems generally. The appropriations involved were modest: $9,500 for the first contract, and $30,000 for the second contract.

As has already been pointed out, beryllium has desirable qualities as a moderator because of its low atomic weight and low neutron-absorption cross section; there was also the possibility that a contribution to the number of neutrons would be realized from the (n, 2n) reaction in beryllium. The value of the cross section was not precisely known; furthermore it was far from certain that any large amount of pure beryllium could be obtained. Allison's problem was essentially similar to the Columbia problem, except for the use of beryllium in place of graphite. Because of the scarcity of beryllium it was suggested that it might be used in conjunction with graphite or some other moderator, possibly as a reflector.

In the Chicago experiments, neutrons produced with the aid of a cyclotron were caused to enter a pile of graphite and beryllium. Allison made a number of measurements on the slowing down and absorption by graphite which were valuable checks on similar experiments at Columbia. He finally was able to obtain enough beryllium to make significant measurements which showed that beryllium was a possible moderator comparable to graphite. However, beryllium was not in fact used at all extensively in view of the great difficulty of producing it in quantity in the required structural form.

This Chicago project as described above became part of the Metallurgical Laboratory project established at the University of Chicago early in 1942.

Setting the Stage for the Greatest Gamble in History

The Chain Reaction Starts

After the group working in Chicago had accumulated a quantity of graphite and uranium ore judged sufficient for the great experiment, and about 6 tons of uranium metal, it was decided to bring the required amounts of material together in the calculated form and see what would happen. A reviewing committee was present, appraising the project. This experiment, says the Report, answered beyond all shadow of doubt the first question before the Metallurgical Laboratory; a self-sustaining nuclear chain reaction had been produced in a system using normal uranium.

The arrangement of material necessary to bring about this unique reaction is described in the fourth appendix to the Smyth Report, which we quote in full.

Description of the Pile

▶ THE ORIGINAL PLAN called for an approximately spherical pile with the best materials near the center. Actually control measurements showed that the critical size had been reached before the sphere was complete, and the construction was modified accordingly. The final structure may be roughly described as an oblate spheroid flattened at the top, i.e., like a door knob. It was desired to have the uranium or uranium oxide lumps spaced in a cubic lattice imbedded in graphite. Consequently, the graphite was cut in bricks and built up in layers, alternate ones of which contained lumps of uranium at the corners of squares. The critical size was reached when the pile had been built to a height only three quarters of that needed according to the most cautions estimates. Consequently only one more layer was added. The graphite used was chiefly from the National Carbon Company and the Speer Graphite Company. The pile contained 12,400 lbs. of metal, part of which was supplied by Westinghouse, part by Metal Hydrides, and part by Ames. Since there were many more lattice points than lumps of metal, the remaining ones were filled with pressed oxide lumps.

For purposes of control and experiment there were ten slots passing completely through the pile. Three of those near the center were used for control and safety rods. Further to facilitate experiment, particularly the removal of samples, one row of bricks carrying uranium and passing near the center of the pile was arranged so that it could be pushed completely out of the pile.

This whole graphite sphere was supported by a timber framework resting on the floor of a squash court under the West Stands of Stagg Field.

Predicted Performance of the Pile

The metal lattice at the center of the pile and the two other major lattices making up the bulk of the rest of the pile had each been studied separately in exponential experiments

No. 18, No. 27, and No. 29. These had given a multiplication factor of 1.07 for the metal lattice and 1.04 and 1.03 for the oxide lattices, the difference in the last two resulting from difference in the grade of graphite used. It is to be remembered that these figures are multiplication factors for lattices of infinite size. Therefore a prediction of the actual effective multiplication factor k_{eff} for the pile as constructed depended on the validity of the deduction of k from the exponential experiments, on a proper averaging for the different lattices and on a proper deduction of k_{eff} from the average k for infinite size. Although the original design of the pile had been deliberately generous, its success when only partly completed indicated that the values of the multiplication factors as calculated from exponential experiments had been too low. The observed effective multiplication factor of the part of the planned structure actually built was about 1.0006 when all neutron absorbers were removed.

Measurements Performed During Construction

A series of measurements was made while the pile was being assembled in order to be sure that the critical dimensions were not reached inadvertently. These measurements served also to check the neutron multiplication properties of the structure during assembly, making possible a prediction of where the critical point would be reached.

In general, any detector of neutrons or gamma radiation can be used for measuring the intensity of the reaction. Neutron detectors are somewhat preferable since they give response more quickly and are not affected by fission-product radiations after shut down. Actually both neutron detectors (boron trifluoride counters) and gamma-ray ionization chambers were distributed in and around the pile. Certain of the ionization chambers were used to operate recording instruments and automatic safety controls.

In the pile itself measurements were made with two types of detector. A boron trifluoride counter was inserted in a slot about 43″ from the ground and its readings taken at frequent intervals. In addition, an indium foil was irradiated every night in a position as close as possible to the effective center of the pile, and its induced activity was measured the following morning and compared with the readings of the boron trifluoride counter.

The results of such measurements can be expressed in two ways. Since the number of secondary neutrons produced by fission will increase steadily as the pile is constructed, the activity A induced in a standard in-

▸ The pile was first operated as a self-sustaining system on December 2, 1942. So far as we know, this was the first time that human beings ever initiated a self-maintaining nuclear chain reaction. Initially the pile was operated at a power level of ½ watt, but on December 12th the power level was raised to 200 watts.

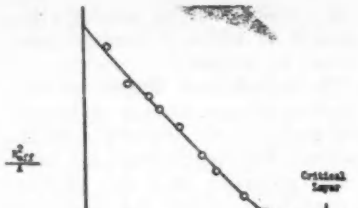


Figure 1

▶ THE CRITICAL LAYER *is reached when the number of neutrons which are available for atom splitting equals the number lost. When the curve cuts the line, available atomic power begins.*

dium foil at the center will increase steadily as the number of layers of the pile is increased. Once the effective multiplication factor is above one, *A* would theoretically increase to infinity. Such an approach to infinity is hard to observe, so a second way of expressing the results was used. Suppose the lattice spacing and purity of materials of a graphite-uranium structure are such that the multiplication factor would be exactly one if the structure were a sphere of infinite radius. Then, for an actual sphere of similar construction but finite radius, the activation of a detector placed at the center would be proportional to the square of the radius. It was possible to determine a corresponding effective radius R_{eff} for the real pile in each of its various stages. It followed, therefore, that, if the factor k_∞ were precisely one on the average for the lattice in the pile, the activity *A* of the detector at the center should increase with increasing R_{eff} in such a way that R^2_{eff}/A remained constant, but, if k_∞ for the lattice were greater than one, then as the pile size approached the critical value, that is, as k_{eff} approached one, *A* should approach infinity and therefore R^2_{eff}/A approach zero. Therefore by extrapolating a curve of R^2_{eff}/A vs. size of the pile, i.e., number of layers, to where it cut the axis, it was possible to predict at what layer k_{eff} would become one. Such a curve, shown in Fig. 1, indicated at what layer the critical size would be reached. The less useful but more direct and dramatic way of recording

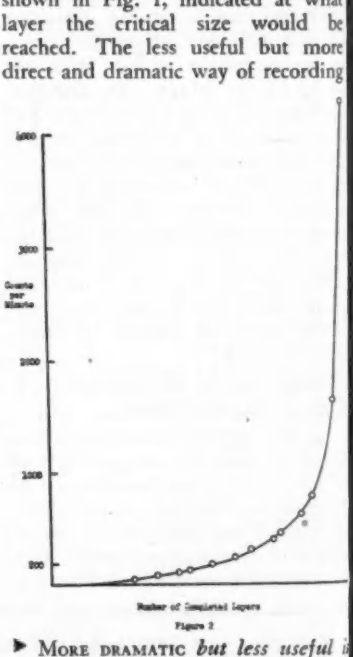


Figure 2

▶ MORE DRAMATIC *but less useful is this method of graphing the same data used for Fig. 1. Growth of neutron activity in the pile as layers are added rises slowly for a little while, then goes up very fast.*

the results is shown in Fig. 2, which shows the growth of the neutron activity of the pile as layers were added.

During the construction, appreciably before reaching this critical layer, some cadmium strips were inserted in suitable slots. They were removed once every day with the proper precautions in order to check the approach to the critical conditions. The construction was carried in this way to the critical layer.

Control

The reaction was controlled by inserting in the pile some strips of neutron absorbing material—cadmium or boron steel. When the pile was not in operation, several such cadmium strips were inserted in a number of slots, bringing the effective multiplication factor considerably below one. In fact, any one of the cadmium strips alone was sufficient to bring the pile below the critical condition. Besides cadmium strips that could be used for manual operation of the pile, two safety rods and one automatic control rod were provided. The automatic control rod was operated by two electric motors responding to an ionization chamber and amplifying system so that, if the intensity of the reaction increased above the desired level, the rod was pushed in, and vice versa.

Operation of the Pile

To operate the pile all but one of the cadmium strips were taken out. The remaining one was then slowly pulled out. As the critical conditions were approached, the intensity of the neutrons emitted by the pile began to increase rapidly. It should be noticed, however, that, when this last strip of cadmium was so far inside the pile that the effective multiplication factor was just below one, it took a rather long time for the intensity to reach the saturation value. Similarly, if the cadmium strip was just far enough out to make k_{eff} greater than one, the intensity rose at a rather slow rate. For example, if one rod is only 1 cm. out from the critical position, the "relaxation time," i.e., the time for the intensity to double is about four hours. These long "relaxation times" were the result of the small percentage of delayed neutrons which have been discussed in Appendix 3,* and make it relatively easy to keep the pile operating at a constant level of intensity.

The pile was first operated on December 2, 1942 to a maximum energy production of about ½ watt. On December 12th the intensity was run up to about 200 watts, but it was not felt safe to go higher because of the danger of the radiation to personnel in and around the building. During this high intensity run, measurements were made of radiation intensity beside the pile, in the building, and on the sidewalk outside.

* See page 40.

Energy Developed by the Pile

In these experiments no direct measurements of energy release were made. The number of neutrons per second emitted by the pile was estimated in terms of the activity of standardized indium foils. Then, from a knowledge of the number of neutrons produced per fission, the resultant rate of energy release (wattage) was calculated.

Possibility of a Fission Bomb And its Destructive Effect

How To Make A Bomb?

The conditions which scientists felt they had to meet, to make a bomb out of materials they had successfully experimented with, were outlined in November 1941 as a guide to further work. The Smyth Report gives them in this form. The transuranian element Plutonium looked promising for the purpose.

Work on Plutonium

➤ In CHAPTER I* mention is made of the suggestion that the element 94, later christened plutonium, would be formed by beta-ray disintegrations of U-239 resulting from neutron absorption by U-238 and that plutonium would probably be an alpha-particle emitter of long half-life and would undergo fission when bombarded by neutrons. In the summer of 1940 the nuclear physics group at the University of California in Berkeley was urged to use neutrons from its powerful cyclotron for the production of plutonium, and to separate it from uranium and investigate its fission properties. Various pertinent experiments were performed by E. Segre, G. T. Seaborg, J. W. Kennedy, and M. H. Wahl at Berkeley prior to 1941 and were reported by E. O. Lawrence to the National Academy Committee in May 1941 and also in a memorandum that was incorporated in the Committee's second report dated July 11, 1941. It will be seen that this memorandum includes one important idea not specifically emphasized by others, namely, the production of large quantities of plutonium for use in a bomb.

* See page 11.

The National Academy Committee Report

The appointment of a National Academy committee was mentioned in Chapter III. The committee's first report in May 1940 mentioned (a) radio-active poisons, (b) atomic power, and (c) atomic bombs, but the emphasis was on power. The second report stressed the importance of the new results on plutonium, but was not specific about the military uses to which the fission process might be put. Both these reports urged that the project be pushed more vigorously.

The third report (November 6, 1941) was specifically concerned with the "possibilities of an explosive fission reaction with U-235." Although neither of the first two National Academy reports indicated that uranium would be likely to be of decisive importance in the present war, this possibility was emphasized in the third report. We can do no better than quote portions of this report.

Since our last report, the progress toward separation of the isotopes of uranium has been such as to make urgent a consideration of (1) the probability of success in the attempt to produce a fission bomb, (2) the destructive effect to be expected from such a bomb, (3) the anticipated time before its develop-

ment can be completed and production be underway, and (4) a preliminary estimate of the costs involved.

1. Conditions for a fission bomb

A fission bomb of superlatively destructive power will result from bringing quickly together a sufficient mass of element U-235. This seems to be as sure as any untried prediction based upon theory and experiment can be.

Our calculations indicate further that the required masses can be brought together quickly enough for the reaction to become efficient. . . .

2. Destructive effect

a. Mass of the bomb. *The mass of U-235 required to produce explosive fission under appropriate conditions can hardly be less than 2 kg nor greater than 100 kg.* These wide limits reflect chiefly the experimental uncertainty in the capture cross section of U-235 for fast neutrons. . . .

b. Energy released by explosive fission. Calculations for the case of masses properly located at the initial instant indicate that between 1 and 5 per cent of the fission energy of the uranium should be released at a fission explosion. This means from 2 to 10×10^8 kilocalories per kg of uranium 235. *The available explosive energy per kg of uranium is thus equivalent to about 300 tons of TNT.*

3. Time required for needed U-235

a. Amount of uranium needed. Since the destructiveness of present bombs is already an important factor in warfare, it is evident that, if the destructiveness of the bombs is thus increased 10,000-fold, they should become of decisive importance.

The amount of uranium required will, nevertheless, be large. If the estimate is correct that 500,000 tons of TNT bombs would be required to devastate Germany's military and industrial objectives, from 1 to 10 tons of U-235 will be required to do the same job.

b. Separation of U-235. *The separation of the isotopes of uranium can be done in the necessary amounts.* Several methods are under development, at least two of which seem definitely adequate, and are approaching the stage of practical test. These are the methods of the centrifuge and of diffusion through porous barriers. Other methods are being investigated or need study which may ultimately prove superior, but are now farther from the engineering stage.

c. Time required for production of fission bombs. An estimate of time required for development, engineering and production of fission bombs can be made only very roughly at this time.

If all possible effort is spent on the program, one might however expect fission bombs to be available in significant quantity within three or four years.

4. Rough estimate of costs

(The figures given in the Academy report under this heading were recognized as only rough estimates since the scientific and engineering data to make them more precise were not available. They showed only that the undertaking would be enormously expensive but still in line with other war expenditures.) . . .

Apparently, the British and the Germans, both grimly at war, thought the problem worth undertaking. Furthermore, the whole national psychology had changed. Although the attack at Pearl Harbor was yet to come, the impending threat of war was much more keenly felt than before, and expenditures of effort and money that would have seemed enormous in 1940 were considered obviously necessary precautions in December 1941. Thus it was not surprising that Bush and his associates felt it was time to push the uranium project vigorously. For this purpose, there was created an entirely new administrative organization which will be described in the next chapter.

Military Possibilities

➤ THE ANNOUNCEMENT of the hypothesis of fission and its experimental confirmation took place in January 1939, as has already been recounted. There was immediate interest in the possible military use of the large amounts of energy released in fission. At that time American-born nuclear physicists were so unaccustomed to the idea of using their science for military purposes that they hardly realized what needed to be done. Consequently the early efforts both at restricting publication and at getting government support were stimulated largely by a small group of foreign-born physicists centering on L. Szilard and including E. Wigner, E. Teller, V. F. Weisskopf, and E. Fermi.

Exchange of Information with the British

➤ PRIOR TO the autumn of 1941 there had been some exchange of reports with the British and some discussion with British scientific representatives who were here on other business. In September 1941, it was decided that Pegram and Urey should get first-hand information by a trip to England. They completed their trip in the first week of December 1941.

In general, work in England had been following much the same lines as in this country. As to the chain-reaction problem, their attention had focussed on heavy water as a moderator rather than graphite; as to isotope separation, they had done extensive work on the diffusion process including the general theory of cascades. Actually the principal importance of this visit and other interchanges during the summer of 1941 lay not in accurate scientific data but in the general scientific impressions. The British, particularly J. Chadwick, were convinced that a U-235 chain reaction could be achieved. They knew that several kilograms of heavy water a day were being produced in Norway, and that Germany had ordered considerable quantities of paraffin to be made using heavy hydrogen; it was difficult to imagine a use for these materials other than in work on the uranium problem. They feared that if the Germans got atomic bombs before the Allies did, the war might be over in a few weeks. The sense of urgency which Pegram and Urey brought back with them was of great importance.

Administration Organization

▶ By the end of 1941 an extensive review of the whole uranium situation had been completed. As a result of this review Bush and his advisers decided to increase the effort on the uranium project and to change the organization. This decision was approved by President Roosevelt. From January 1942 until early summer of 1942 the uranium work was directed by Bush and Conant working with the Program Chiefs and a Planning Board. In the summer of 1942 the Army, through the Corps of Engineers, was assigned an active part in the procurement and engineering phases, organizing the Manhattan District for the purpose. In September 1942, Dr. Bush, Dr. Conant, General Styer, and Admiral Purnell were appointed as a Military Policy Committee to determine the general policies of the whole project. Also in September, General Groves was appointed to take charge of all Army activities of the project. The period of joint OSRD and Army control continued through April 1943 with the Army playing an increasingly important role as the industrial effort got fully under way. In May 1943 the research contracts were transferred to the Corps of Engineers; the period of joint OSRD-Army control ended and the period of complete Army control began.

Since 1943 there have been no important changes in the form of the organization and few of importance in the operating personnel. General Groves has continued to carry the major responsibility for correlating the whole effort and keeping it directed toward its military objectives. It has been his duty to keep the various parts of the project in step, to see that raw materials were available for the various plants, to determine production schedules, to make sure that the development of bomb design kept up with production schedules, to arrange for use of the bombs when the time came, and to maintain an adequate system of security. In discharging these duties General Groves has had the help of his tremendous organization made up of civilian scientists and engineers and Engineer officers and enlisted men. Many of the civilians have been mentioned already or will be mentioned in later chapters dealing with particular projects. Brigadier General T. F. Farrell has acted as General Groves' deputy in the important later phases of the project. Colonel K. D. Nichols, the District Engineer of the Manhattan District with his headquarters at the Clinton Engineer Works, has been connected with the project since 1942. He has been concerned with the research and production problems of both U-235 and plutonium and has always shown exceptional understanding of the technical problems and their relative importance. Two other officers who should be mentioned are Colonel F. T. Matthias and Colonel S. L. Warren. Colonel Matthias has discharged major responsibilities at the Hanford Engineer Works in an extremely able manner; his duties have been concerned with both the construction and operational phases of the project. Colonel Warren is chief of the Medical Section of the Manhattan District.

Old Conservation Laws Fade Into New Combined Principle

Mass and Energy

If energy may sometimes be converted into matter and matter into energy, what becomes of the principles cherished by physicists and chemists for so many years, that neither matter nor energy can be created or destroyed? As usual in the development of scientific laws, these axioms dissolve into a wider law. The scientists who wrote the Smyth Report began their explanation of atomic energy with the following clarification of theory.

The Conservation of Mass and of Energy

▶ THERE ARE two principles that have been cornerstones of the structure of modern science. The first—that matter can be neither created nor destroyed but only altered in form—was enunciated in the eighteenth century and is familiar to every student of chemistry; it has led to the principle known as the law of conservation of mass. The second—that energy can be neither created nor destroyed but only altered in form—emerged in the nineteenth century and has ever since been the plague of inventors of perpetual-motion machines; it is known as the law of conservation of energy.

These two principles have constantly guided and disciplined the development and application of science. For all practical purposes they were unaltered and separate until some five years ago. For most practical purposes they are still so, but it is now known that they are, in fact, two phases of a single principle for we have discovered that energy may sometimes be converted into matter and matter into energy. Specifically, such a conversion is observed in the phenomenon of nuclear fission of uranium, a process in which atomic nuclei split into fragments with the release of an enormous amount of energy. The military use of this energy has been the object of the research and production projects described in this report.

The Equivalence of Mass and Energy

One conclusion that appeared rather early in the development of the theory of relativity was that the inertial mass of a moving body increased as its speed increased. This implied an equivalence between an increase in energy of motion of a body, that is, its kinetic energy, and an increase in its mass. To most practical physicists and engineers this appeared a mathematical fiction of no practical importance. Even Einstein could hardly have foreseen the present applications, but as early as 1905 he did clearly state that mass and energy were equivalent and suggested that proof of this equivalence might be found by the study of radioactive substances. He concluded that the amount of energy, E, equivalent to a mass, m, was given by the equation

$$E = mc^2$$

where c is the velocity of light. If

this is stated in actual numbers, its startling character is apparent. It shows that one kilogram (2.2 pounds) of matter, if converted entirely into energy, would give 25 billion kilowatt hours of energy. This is equal to the energy that would be generated by the total electric power industry in the United States (as of 1939) running for approximately two months. Compare this fantastic figure with the 8.5 kilowatt hours of heat energy which may be produced by burning an equal amount of coal.

The extreme size of this conversion figure was interesting in several respects. In the first place, it explained why the equivalence of mass and energy was never observed in ordinary chemical combustion. We now believe that the heat given off in such a combustion has mass associated with it, but this mass is so small that it cannot be detected by the most sensitive balances available. (It is of the order of a few billionths of a gram per mole.) In the second place, it was made clear that no appreciable quantities of matter were being converted into energy in any familiar terrestrial processes, since no such large sources of energy were known. Further, the possibility of initiating or controlling such a conversion in any practical way seemed very remote. Finally, the very size of the conversion factor opened a magnificent field of speculation to philosophers, physicists, engineers, and comic-strip artists. For twenty-five years such speculation was unsupported by direct experimental evidence, but beginning about 1930 such evidence began to appear in rapidly increasing quantity. Before discussing such evidence and the practical partial conversion of matter into energy that is our main theme, we shall review the foundations of atomic and nuclear physics. General familiarity with the atomic nature of matter and with the existence of electrons is assumed. Our treatment will be little more than an outline which may be elaborated by reference to books such as Pollard and Davidson's *Applied Nuclear Physics* and Stranathan's *The Particles of Nuclear Physics*.

Atomic Power in 1939

▸ We have talked glibly about the equivalence of mass and energy and about nuclear reactions, such as that of protons on lithium, where energy was released in relatively large amounts. Now let us ask why atomic power plants did not spring up all over the world in the thirties. After all, if we can get 2.76×10^{-5} ergs from an atom of lithium struck by a proton, we might expect to obtain approximately half a million kilowatt hours by combining a gram of hydrogen with seven grams of lithium. It looks better than burning coal. The difficulties are in producing the high-speed protons and in controlling the energy produced. All the experiments we have been talking about have been done with very small quantities of material—not tons or pounds or grams, but fractions of micrograms. The amount of energy used up in the experiment was always far greater than the amount generated by the nuclear reaction.

Radioactivity is the Key To Happenings Within the Atom

Radioactivity

How radioactivity was discovered and what has come of it is covered in this section of the Smyth Report.

Radioactivity and Atomic Structure

▶ First discovered by H. Becquerel in 1896 and subsequently studied by Pierre and Marie Curie, E. Rutherford, and many others, the phenomena of radioactivity have played leading roles in the discovery of the general laws of atomic structure and in the verification of the equivalence of mass and energy.

Ionization by Radioactive Substances

The first observed phenomenon of radioactivity was the blackening of photographic plates by uranium minerals. Although this effect is still used to some extent in research on radioactivity, the property of radioactive substances that is of greatest scientific value is their ability to ionize gases. Under normal conditions air and other gases do not conduct electricity — otherwise power lines and electrical machines would not operate in the open as they do. But under some circumstances the molecules of air are broken apart into positively and negatively charged fragments, called ions. Air thus ionized does conduct electricity. Within a few months after the first discovery of radioactivity Becquerel found that uranium had the power to ionize air. Specifically he found that the charge on an electroscope would leak away rapidly through the air if some uranium salts were placed near it. (The same thing would happen to a storage battery if sufficient radioactive material were placed near by.) Ever since that time the rate of discharge of an electroscope has served as a measure of intensity of radioactivity. Furthermore, nearly all present-day instruments for studying radioactive phenomena depend on this ionization effect directly or indirectly. An elementary account of such instruments, notably electroscopes, Geiger Müller counters, ionization chambers, and Wilson cloud chambers is given in Appendix 1.*

The Different Radiations

Evidence that different radioactive substances differ in their ionizing power both in kind and in intensity indicates that there are differences in the "radiations" emitted. Some of the radiations are much more penetrating than others; consequently, two radioactive samples having the same effect on an "unshielded" electroscope may have very different effects if the electroscope is "shielded," i.e., if screens are interposed between the sample and the electroscope. These screens are said to absorb the radiation.

Studies of absorption and other phenomena have shown that in fact there are three types of "radiation" given off by radioactive substances. There are alpha particles,

* To appear in a later issue of Chemistry.

which are high-speed ionized helium atoms (actually the nuclei of helium atoms), beta particles, which are high-speed electrons, and gamma rays, which are electromagnetic radiation similar to X-rays. Of these only the gamma rays are properly called radiations, and even these act very much like particles because of their short wave-length. Such a "particle" or quantum of gamma radiation is called a photon. In general, the gamma rays are very penetrating, the alpha and beta rays less so. Even though the alpha and beta rays are not very penetrating, they have enormous kinetic energies for particles of atomic size, energies thousands of times greater than the kinetic energies which the molecules of a gas have by reason of their thermal motion, and thousands of times greater than the energy changes per atom in chemical reactions. It was for this reason that Einstein suggested that studies of radioactivity might show the equivalence of mass and energy.

Separation of Isotopes

➤ It is well known that the molecules of a gas or liquid are in continual motion and that their average kinetic energy depends only on the temperature, not on the chemical properties of the molecules. Thus in a gas made up of a mixture of two isotopes the average kinetic energy of the light molecules and of the heavy ones is the same. Since the kinetic energy of a molecule is $\frac{1}{2}$ mv^2, where m is the mass and v the speed of the molecule, it is apparent that on the average the speed of a lighter molecule must be greater than that of a heavier molecule. Therefore, at least in principle, any process depending on the average speed of molecules can be used to separate isotopes. Unfortunately, the average speed is inversely proportional to the *square root* of the mass so that the difference is very small for the gaseous compounds of the uranium isotopes. Also, although the *average* speeds differ, the ranges of speed show considerable overlap. In the case of the gas uranium hexafluoride, for example, over 49 per cent of the light molecules have speeds as low as those of 50 per cent of the heavy molecules.

Obviously there is no feasible way of applying mechanical forces directly to molecules individually; they cannot be poked with a stick or pulled with a string. But they are subject to gravitational fields and, if ionized, may be affected by electric and magnetic fields. Gravitational forces are, of course, proportional to the mass. In a very high vacuum U-235 atoms and U-238 atoms would fall with the same acceleration, but just as a feather and a stone fall at very different rates in air where there are frictional forces resisting motion, there may be conditions under which a combination of gravitational and opposing inter-molecular forces will tend to move heavy atoms differently from light ones. Electric and magnetic fields are more easily controlled than gravitational fields or "pseudo-gravitational" fields (i.e., centrifugal-force fields) and are very effective in separating ions of differing masses.

How the Atom is Constructed And How it Disintegrates

The Atom

Some elements are different, but have the same atomic weight. For these scientists working on the atomic power project have coined the needed term "isobars." The name complements "isotope" for elements which are the same but whose atomic weights are different.

➤ BEFORE considering what types of atoms emit alpha, beta, and gamma rays, and before discussing the laws that govern such emission, we shall describe the current ideas on how atoms are constructed, ideas based partly on the study of radioactivity.

According to our present view every atom consists of a small heavy nucleus approximately 10^{-12} cm in diameter surrounded by a largely empty region 10^{-8} cm in diameter in which electrons move somewhat like planets about the sun. The nucleus carries an integral number of positive charges, each 1.6×10^{-19} coulombs in size. Each electron carries one negative charge of this same size, and the number of electrons circulating around the nucleus is equal to the number of positive charges on the nucleus so that the atom as a whole has a net charge of zero.

Atomic Number and Electronic Structure

The number of positive charges in the nucleus is called the atomic number, Z. It determines the number of electrons in the extranuclear structure, and this in turn determines the chemical properties of the atom. Thus all the atoms of a given chemical element have the same atomic number, and conversely all atoms having the same atomic number are atoms of the same element regardless of possible differences in their nuclear structure. The extranuclear electrons in an atom arrange themselves in successive shells according to well-established laws. Optical spectra arise from disturbances in the outer parts of this electron structure; X-rays arise from disturbances of the electrons close to the nucleus. The chemical properties of an atom depend on the outermost electrons, and the formation of chemical compounds is accompanied by minor rearrangements of these electronic structures. Consequently, when energy is obtained by oxidation, combustion, explosion, or other chemical processes, it is obtained at the expense of these structures so that the arrangement of the electrons in the products of the process must be one of lowered energy content. (Presumably the total mass of these products is correspondingly lower but not detectably so.) The atomic nuclei are not affected by any chemical process.

Mass Number

Not only is the positive charge on a nucleus always an integral number of electronic charges, but the mass of the nucleus is always approximately a whole number times a fundamental unit of mass which is almost the mass of a proton, the nucleus of a hydro-

gen atom. This whole number is called the mass number, A, and is always at least twice as great as the atomic number except in the cases of hydrogen and a rare isotope of helium. Since the mass of a proton is about 1800 times that of an electron, the mass of the nucleus is very nearly the whole mass of the atom.

Isotopes and Isobars

Two species of atoms having the same atomic number but different mass numbers are called isotopes. They are chemically identical, being merely two species of the same chemical element. If two species of atoms have the same mass number but different atomic numbers, they are called isobars and represent two different chemical elements.

Nuclear Change

If an atom emits an alpha particle (which has an atomic number of two and a mass of four), it becomes an atom of a different element with an atomic number lower by two and a mass number lower by four. The emission by a nucleus of a beta particle increases the atomic number by one and leaves the mass number unaltered. In some cases, these changes are accompanied by the emission of gamma rays. Elements which spontaneously change or "disintegrate" in these ways are unstable and are described as being "radioactive." The only natural elements which exhibit this property of emitting alpha or beta particles are (with a few minor exceptions) those of very high atomic numbers and mass numbers, such as uranium, thorium, radium, and actinium, i.e., those known to have the most complicated nuclear structures.

Half-Lives; The Radioactive Series

All the atoms of a particular radioactive species have the same probability of disintegrating in a given time, so that an appreciable sample of radioactive material, containing many millions of atoms, always changes or "disintegrates" at the same rate. This rate at which the material changes is expressed in terms of the "half-life," the time required for one half the atoms initially present to disintegrate, which evidently is constant for any particular atomic species. Half-lives of radioactive materials range from fractions of a second for the most unstable to billions of years for those which are only slightly unstable. Often, the "daughter" nucleus like its radioactive "parent" is itself radioactive and so on down the line for several successive generations of nuclei until a stable one is finally reached. There are three such families or series comprising all together about forty different radioactive species. The radium series starts from one isotope of uranium, the actinium series from another isotope of uranium, and the thorium series from thorium. The final product of each series, after ten or twelve successive alpha and beta particle emissions, is a stable isotope of lead.

Artificial Nuclear Disintegration

Before 1919 no one had succeeded in disturbing the stability of ordinary nuclei or affecting the disintegration rates of those that were naturally radioactive. In 1919 Rutherford showed that high-energy alpha particles could cause an alteration in the nucleus of an ordinary element. Specifically he

succeeded in changing a few atoms of nitrogen into atoms of oxygen by bombarding them with alpha particles. The process involved may be written as

$$He^4 + N^{14} \rightarrow O^{17} + H^1$$

meaning that a helium nucleus of mass number 4 (an alpha particle) striking a nitrogen nucleus of mass number 14 produces an oxygen nucleus of mass number 17 and a hydrogen nucleus of mass number 1. The hydrogen nucleus, known as the "proton," is of special importance since it has the smallest mass of any nucleus. Although protons do not appear in natural radioactive processes, there is much direct evidence that they can be knocked out of nuclei.

Fortunate Time Lag of Neutrons Allows Fission Control in Pile

Delayed Neutrons

➤ WE SHALL NOT mention a majority of the various auxiliary experiments. There was one, however—the study of delayed neutrons—that we shall discuss because it is a good example of the kind of experiment that had to be performed and because it concerned one effect, not heretofore mentioned, that is of great importance in controlling a chain-reacting pile.

From previous investigations, some of which were already published, it was known that about 1 per cent of the neutrons emitted in fission processes were not ejected immediately but were given off in decreasing quantity over a period of time, a fact reminiscent of the emission of beta rays from shortlived radioactive substances. Several half-lives had been observed, the longest being of the order of a minute.

It was realized early that this time delay gave a sort of inertia to the chain reaction that should greatly facilitate control. If the effective multiplication factor of a pile became slightly greater than one, the neutron density would not rise to harmfully large values almost instantly but would rise gradually so that there would be a chance for controls to operate. (Other time intervals involved, such as those between collisions, are too small to be useful.)

Because of the importance of this effect of delayed neutrons for control it was decided to repeat and improve the earlier measurements. (The fact that this was a repetition rather than a new measurement is also typical of much of the work in physics in this period.) The results indicated that 1.0 per cent of the neutrons emitted in uranium fission are delayed by at least 0.01 second and that about 0.07 per cent are delayed by as much as a minute. By designing a pile such that the effective value of k, the multiplication factor, is only 1.01 the number of delayed neutrons is sufficient to allow easy control.

New Atomic Team Member Is Uncharged Particle

The Neutron

From polonium to beryllium to paraffin was the play which called attention to the new member of the atomic team. To change the metaphor, the Smyth Report says the neutron is the theme song of the whole atomic power research.

IN THE decade following Rutherford's work many similar experiments were performed with similar results. One series of experiments of this type led to the discovery of the neutron, which will be discussed in some detail since the neutron is practically the theme song of this whole project.

In 1930 W. Bothe and H. Becker in Germany found that if the very energetic natural alpha particles from polonium fell on certain of the light elements, specifically beryllium, boron or lithium, an unusually penetrating radiation was produced. At first this radiation was thought to be gamma radiation although it was more penetrating than any gamma rays known, and the details of experimental results were very difficult to interpret on this basis. The next important contribution was reported in 1932 by Irene Curie and F. Joliot in Paris. They showed that if this unknown radiation fell on paraffin or any other hydrogen-containing compound it ejected protons of very high energy. This was not in itself inconsistent with the assumed gamma-ray nature of the new radiation, but detailed quantitative analysis of the data became increasingly difficult to reconcile with such an hypothesis. Finally (later in 1932) J. Chadwick in England performed a series of experiments showing that the gamma ray hypothesis was untenable. He suggested that in fact the new radiation consisted of uncharged particles of approximately the mass of the proton, and he performed a series of experiments verifying his suggestion. Such uncharged particles are now called neutrons.

The one characteristic of neutrons which differentiates them from other subatomic particles is the fact that they are uncharged. This property of neutrons delayed their discovery, makes them very penetrating, makes it impossible to observe them directly, and makes them very important as agents in nuclear change. To be sure, an atom in its normal state is also uncharged, but it is ten thousand times larger than a neutron and consists of a complex system of negatively charged electrons widely spaced around a positively charged nucleus. Charged particles (such as protons, electrons, or alpha particles) and electromagnetic radiations (such as gamma rays) lose energy in passing through matter. They exert electric forces which ionize atoms of the material through which they pass. (It is such ionization processes that make the air electrically conducting in the path of electric sparks and lightning flashes.) The energy taken up in ionization equals the energy lost by

the charged particle, which slows down, or by the gamma ray, which is absorbed. The neutron, however, is unaffected by such forces; it is affected only by a very short-range force, i.e., a force that comes into play when the neutron comes very close indeed to an atomic nucleus. This is the kind of force that holds a nucleus together in spite of the mutual repulsion of the positive charges in it. Consequently a free neutron goes on its way unchecked until it makes a "head-on" collision with an atomic nucleus. Since nuclei are very small, such collisions occur but rarely and the neutron travels a long way before colliding. In the case of a collision of the "elastic" type, the ordinary laws of momentum apply as they do in the elastic collision of billiard balls. If the nucleus that is struck is heavy, it acquires relatively little speed, but if it is a proton, which is approximately equal in mass to the neutron, it is projected forward with a large fraction of the original speed of the neutron, which is itself correspondingly slowed. Secondary projectiles resulting from these collisions may be detected, for they are charged and produce ionization. The uncharged nature of the neutron makes it not only difficult to detect but difficult to control. Charged particles can be accelerated, decelerated, or deflected by electric or magnetic fields which have no effect on neutrons. Furthermore, free neutrons can be obtained only from nuclear disintegrations; there is no natural supply. The only means we have of controlling free neutrons is to put nuclei in their way so that they will be slowed and deflected or absorbed by collisions. As we shall see, these effects are of the greatest practical importance.

The Positron And the Deuteron

The year 1932 brought the discovery not only of the neutron but also of the positron. The positron was first observed by C. D. Anderson at the California Institute of Technology. It has the same mass and the same magnitude of charge as the electron, but the charge is positive instead of negative. Except as a particle emitted by artificially radioactive nuclei, it is of little interest to us.

One other major discovery marked the year 1932. H. C. Urey, F. G. Brickwedde, and G. M. Murphy found that hydrogen had an isotope of mass number 2, present in natural hydrogen to one part in 5000. Because of its special importance this heavy species of hydrogen is given a name of its own, deuterium, and the corresponding nucleus is called the deuteron. Like the alpha particle it is not one of the fundamental particles but does play an important role in certain processes for producing nuclear disintegration.

Nuclear Structure

The idea that all elements are made out of a few fundamental particles is an old one. It is now firmly established. We believe that there are three fundamental particles—the neutron, the proton, and the electron. A complete treatise would also discuss the positron, which we have mentioned, the neutrino and the mesotron. The deuteron and alpha particle, which have already been mentioned, are important complex particles.

According to our present views the nuclei of all atomic species are made up of neutrons and protons. The number of protons is equal to the atomic number, Z. The number of neutrons, N, is equal to the difference between the mass number and the atomic number, or $A - Z$. There are two sets of forces acting on these particles, ordinary electric coulomb forces of repulsion between the positive charges and very short-range forces of attraction between all the particles. These last forces are only partly understood, and we shall not attempt to discuss them. Suffice it to say that combined effects of these attractive and repulsive forces are such that only certain combinations of neutrons and protons are stable. If the neutrons and protons are few in number, stability occurs when their numbers are about equal. For larger nuclei, the proportion of neutrons required for stability is greater. Finally, at the end of the periodic table, where the number of protons is over 90 and the number of neutrons nearly 150, there are no completely stable nuclei. (Some of the heavy nuclei are almost stable as evidenced by very long half-lives.) If an unstable nucleus is formed artificially by adding an extra neutron or proton, eventually a change to a stable form occurs. Strangely enough, this is not accomplished by ejecting a proton or a neutron but by ejecting a positron or an electron; apparently within the nucleus a proton converts itself to a neutron and positron (or a neutron converts itself into a proton and electron), and the light charged particle is ejected. In other words, the mass number remains the same but the atomic number changes. The stability conditions are not very critical so that for a given mass number, ie., given total number of protons and neutrons, there may be several stable arrangements of protons and neutrons (at most three or five) giving several isobars. For a given atomic number, i.e., given number of protons, conditions can vary still more widely so that some of the heavy elements have as many as ten or twelve stable isotopes. Some two hundred and fifty different stable nuclei have been identified, ranging in mass number from one to two hundred and thirty-eight and in atomic number from one to ninety-two.

All the statements we have been making are based on experimental evidence. The theory of nuclear forces is still incomplete, but it has been developed on quantum-mechanical principles sufficiently to explain not only the above observations but more detailed empirical data on artificial radioactivity and on differences between nuclei with odd and even mass numbers.

Artificial Radioactivity

We mentioned above the emission of positrons or electrons by nuclei seeking stability. Electron emission (beta rays) was already familar in the study of naturally radioactive substances, but positron emission was not found in the case of such substances. In fact, the general discussion presented above obviously was based in part on information that cannot be presented in this report. We shall, however, give a brief account of the discovery of "artificial" radioactivity and what is now known about it.

In 1934, Curie and Joliot reported that certain light elements (boron,

magnesium, aluminum) which had been bombarded with alpha particles continued to emit positrons for some time after the bombardment was stopped. In other words, alpha-particle bombardment produced radioactive forms of boron, magnesium, and aluminum. Curie and Joliot actually measured half-lives of 14 minutes, 2.5 minutes, and 3.25 minutes, respectively, for the radioactive substances formed by the alpha-particle bombardment.

This result stimulated similar experiments all over the world. In particular, E. Fermi reasoned that neutrons, because of their lack of charge, should be effective in penetrating nuclei, especially those of high atomic number which repel protons and alpha particles strongly. He was able to verify his prediction almost immediately, finding that the nucleus of the bombarded atom captured the neutron and that there was thus produced an unstable nucleus which then achieved stability by emitting an electron. Thus, the final, stable nucleus was one unit higher in mass number and one unit higher in atomic number than the initial target nucleus.

As a result of innumerable experiments carried out since 1934, radioactive isotopes of nearly every element in the periodic table can now be produced. Some of them revert to stability by the emission of positrons, some by the emission of electrons, some by a process known as K-electron capture which we shall not discuss, and a small number (probably three) by alpha particle emission. Altogether some five hundred unstable nuclear species have been observed, and in most cases their atomic numbers and mass numbers have been identified.

Not only do these artificially radioactive elements play an important role throughout the project with which we are concerned, but their future value in medicine, in "tracer" chemistry, and in many other fields of research can hardly be overestimated.

Health Hazards

▶ IT HAD BEEN known for a long time that radioactive materials were dangerous. They give off very penetrating radiations—gamma rays—which are much like X-rays in their physiological effects. They also give off beta and alpha rays which, although less penetrating, can still be dangerous. The amounts of radium used in hospitals and in ordinary physical measurements usually comprise but a few milligrams. The amounts of radioactive material produced by the fission of uranium in a relatively small chain-reacting system may be equivalent to hundreds or thousands of grams of radium. A chain-reacting system also gives off intense neutron radiation known to be comparable to gamma rays as regards health hazards. Quite apart from its radioactive properties, uranium is poisonous chemically. Thus, nearly all work in this field is hazardous—particularly work on chain reactions and the resulting radioactive products.

Nuclear Binding Energies Equivalent to Mass Difference

Energy

The total mass of a stable nucleus is less than the total mass of the separate protons and neutrons it is made of. Tiny differences in the second and third decimal places are the significant figures of atomic power. The Smyth Report goes on to the energy side of the picture.

▶ In describing radioactivity and atomic structure we have deliberately avoided quantitative data and have not mentioned any applications of the equivalence of mass and energy which we announced as the guiding principle of this report. The time has now come when we must speak of quantitative details, not merely of general principles.

We have spoken of stable and unstable nuclei made up of assemblages of protons and neutrons held together by nuclear forces. It is a general principal of physics that work must be done on a stable system to break it up. Thus, if an assemblage of neutrons and protons is stable, energy must be supplied to separate its constituent particles. If energy and mass are really equivalent, then the total mass of a stable nucleus should be less than the total mass of the separate protons and neutrons that go to make it up. This mass difference, then, should be equivalent to the energy required to disrupt the nucleus completely, which is called the binding energy. Remember that we said that the masses of all nuclei were "approximately" whole numbers. It is the small differences from whole numbers that are significant.

Consider the alpha particle as an example. It is stable; since its mass number is four and its atomic number two it consists of two protons and two neutrons. The mass of a proton is 1.00758 and that of a neutron is 1.00893, so that the total mass of the separate components of the helium nucleus is

$2 \times 1.00758 + 2 \times 1.00893 = 4.03302$

whereas the mass of the helium nucleus itself is 4.00280. Neglecting the last two decimal places we have 4.033 and 4.003, a difference of 0.030 mass units. This, then, represents the "binding energy" of the protons and neutrons in the helium nucleus. It looks small, but recalling Einstein's equation, $E = mc^2$, we remember that a small amount of mass is equivalent to a large amount of energy. Actually 0.030 mass units is equal to 4.5×10^{-5} ergs per nucleus or 2.7×10^{19} ergs per gram molecule of helium. In units more familiar to the engineer or chemist, this means that to break up the nuclei of all the helium atoms in a gram of helium would require 1.62×10^{11} gram calories or 190,000 kilowatt hours of energy. Conversely, if free protons and neutrons could be assembled into helium nuclei, this energy would be released.

Evidently it is worth exploring the possibility of getting energy by combining protons and neutrons or by

Atomic Projectiles Cause Rearrangement of Nucleus

Reactions of the Nucleus

The process of rearrangement within the atom goes on until a stable type of element is reached. The chapter on mass and energy of the Smyth Report summarizes these processes, and explains how mass and energy nevertheless remain constant.

Nuclear Bombardment

➤ COCKCROFT AND WALTON produced protons of fairly high energy by ionizing gaseous hydrogen and then accelerating the ions in a transformer-rectifier high-voltage apparatus. A similar procedure can be used to produce high-energy deuterons from deuterium or high-energy alpha particles from helium. Higher energies can be attained by accelerating the ions in cyclotrons or Van de Graaff machines. However, to obtain high-energy gamma radiation or—most important of all—high-energy neutrons, nuclear reactions themselves must be used as sources. Radiations of sufficiently high energy come from certain naturally radioactive materials or from certain bombardments. Neutrons are commonly produced by the bombardment of certain elements, notably beryllium or boron, by natural alpha particles, or by bombarding suitable targets with protons or deuterons. The most common source of neutrons is a mixture of radium and beryllium where the alpha particles from radium and its decay products penetrate the Be^9 nuclei, which then give off neutrons and become stable C^{12} nuclei (ordinary carbon). A frequently used "beam" source of neutrons results from accelerated deuterons impinging on "heavy water" ice. Here the high-speed deuterons strike the target deuterons to produce neutrons and He^3 nuclei. Half a dozen other reactions are also used involving deuterium, lithium, beryllium, or boron as targets. Note that in all these reactions the total mass number and total charge number are unchanged.

To summarize, the agents that are found to initiate nuclear reactions are—in approximate order of importance—neutrons, deuterons, protons, alpha particles, gamma rays and, rarely, heavier particles.

Nuclear Bombardment Results

Most atomic nuclei can be penetrated by at least one type of atomic projectile (or by gamma radiation). Any such penetration may result in a nuclear rearrangement in the course of which a fundamental particle is ejected or radiation is emitted or both. The resulting nucleus may be one of the naturally available stable species, or—more likely—it may be an atom of a different type which is radioactive, eventually changing to still a different nucleus. This may in turn be radioactive and, if so, will again decay. The process continues until all nuclei have changed to a stable type. There are two respects in which these artificially radioactive substances differ from the natural ones: many of them change by emitting positrons (unknown in natural radioactivity) and very few of the

emit alpha particles. In every one of the cases where accurate measurements have been made, the equivalence of mass and energy has been demonstrated and the mass-energy total has remained constant. (Sometimes it is necessary to invoke neutrinos to preserve mass-energy conservation.)

Notation

A complete description of a nuclear reaction should include the nature, mass and energy of the incident particle, also the nature (mass number and atomic number), mass and energy (usually zero) of the target particle, also the nature, mass and energy of the ejected particles (or radiation), and finally the nature, mass and energy of the remainder. But all of these are rarely known and for many purposes their complete specification is unnecessary. A nuclear reaction is frequently described by a notation that designates first the target by chemical symbol and mass number if known, then the projectile, then the emitted particle, and then the remainder. In this scheme the neutron is represented by the letter n, the proton by p, the deuteron by d, the alpha particle by α, and the gamma ray by γ. Thus the radium-beryllium neutron reaction can be written Be^9 $(\alpha,n)C^{12}$ and the deuteron-deuteron reaction $H^2(d,n)He^3$.

Types of Reaction

Considering the five different particles (n, p, d, α, γ) both as projectiles and emitted products, we might expect to find twenty-five combinations possible. Actually the deuteron very rarely occurs as a product particle, and the photon (*sic*) initiates only two types of reaction. There are, however, a few other types of reaction such as (n,2n), (d,H^3), and fission, which bring the total known types to about twenty-five. Perhaps the (n,γ) reaction should be specifically mentioned as it is very important in one process which will concern us. It is often called "radiative capture" since the neutron remains in the nucleus and only a gamma ray comes out.

Probability and Cross Section

So far nothing has been said about the probability of nuclear reactions. Actually it varies widely. There is no guarantee that a neutron or proton headed straight for a nucleus will penetrate it at all. It depends on the nucleus and on the incident particle. In nuclear physics, it is found convenient to express probability of a particular event by a "cross section." Statistically, the centers of the atoms in a thin foil can be considered as points evenly distributed over a plane. The center of an atomic projectile striking this plane has geometrically a definite probability of passing within a certain distance (r) of one of these points. In fact, if there are n atomic centers in an area A of the plane, this probability is $n \pi r^2/A$, which is simply the ratio of the aggregate area of circles of radius r drawn around the points to the whole area. If we think of the atoms as impenetrable steel discs and the impinging particle as a bullet of negligible diameter, this ratio is the probability that the bullet will strike a steel disc, i.e., that the atomic projectile will be stopped by the foil. If it is the fraction of impinging atoms getting through the foil which is measured, the result can still be expressed in terms of the equivalent stopping cross

section of the atoms. This notion can be extended to any interaction between the impinging particle and the atoms in the target. For example, the probability that an alpha particle striking a beryllium target will produce a neutron can be expressed as the equivalent cross section of beryllium for this type of reaction.

In nuclear physics it is conventional to consider that the impinging particles have negligible diameter. The technical definition of cross section for any nuclear process is therefore:

$$\frac{\text{number of processes occurring}}{\text{number of incident particles}}$$

(number of target nuclei per cm^2) $\times$ (nuclear cross section in cm^2).

It should be noted that this definition is for the cross section per nucleus. Cross sections can be computed for any sort of process, such as capture, scattering, production of neutrons, etc. In many cases, the number of particles emitted or scattered in nuclear processes is not measured directly; one merely measures the attenuation produced in a parallel beam of incident particles by the interposition of a known thickness of a particular material. The cross section obtained in this way is called the total cross section and is usually denoted by σ.

As indicated in a previous paragraph, the typical nuclear diameter is of the order of 10^{-12} cm. We might therefore expect the cross sections for nuclear reactions to be of the order of $\pi d^2/4$ or roughly 10^{-24} cm^2 and this is the unit in which they are usually expressed. Actually the observed cross sections vary enormously. Thus for slow neutrons absorbed by the (n,γ) reaction the cross section in some cases is as much as 1000×10^{-24} cm^2, while the cross sections for transmutations by gamma-ray absorption are in the neighborhood of $(1/1000) \times 10^{-24}$ cm^2.

Purification of Uranium

➤ EXPERIMENTS at the National Bureau of Standards by J. I. Hoffman demonstrated that, by the use of an ether extraction method, all the impurities are removed by a single extraction of uranyl nitrate. The use of this method removed the great bulk of the difficulties in securing pure oxide and pure materials for the production of the metal. Early in May 1942, arrangements were completed with the Mallinckrodt Chemical Works in St. Louis to put the new grade of oxide through an ether extraction process on a production basis for a further reduction in impurity content and to deliver the final product as brown dioxide. Deliveries started in July 1942 at a rate of 30 tons a month. This oxide is now used as a starting point for all metal production, and no higher degree of purity can be expected on a commercial scale. In fact, it was a remarkable achievement to have developed and put into production on a scale of the order of one ton per day a process for transforming grossly impure commercial oxide to oxide of a degree of purity seldom achieved even on a laboratory scale.

Wise Decisions Necessary In Use of Appalling Power

What of the Future?

The Smyth Report, "A General Account of the Development of Methods of Using Atomic Energy for Military Purposes Under the Auspices of the United States Government 1940-1945," closes with a plea to men of science to help their fellow citizens use wisely for the good of the human race the power they have unlocked. Otherwise "civilization would have the means to commit suicide at will."

▶ As THE RESULT of the labors of the Manhattan District organization in Washington and in Tennessee, of the scientific groups at Berkeley, Chicago, Columbia, Los Alamos, and elsewhere, of the industrial groups at Clinton, Hanford, and many other places, the end of June 1945 finds us expecting from day to day to hear of the explosion of the first atomic bomb devised by man. All the problems are believed to have been solved at least well enough to make a bomb practicable. A sustained neutron chain reaction resulting from nuclear fission has been demonstrated; the conditions necessary to cause such a reaction to occur explosively have been established and can be achieved; production plants of several different types are in operation, building up a stock pile of the explosive material. Although we do not know when the first explosion will occur nor how effective it will be, announcement of its occurrence will precede the publication of this report. Even if the first attempt is relatively ineffective, there is little doubt that later efforts will be highly effective; the devastation from a single bomb is expected to be comparable to that of a major air raid by usual methods.

A weapon has been developed that is potentially destructive beyond the wildest nightmares of the imagination; a weapon so ideally suited to sudden unannounced attack that a country's major cities might be destroyed overnight by an ostensibly friendly power. This weapon has been created not by the devilish inspiration of some warped genius but by the arduous labor of thousands of normal men and women working for the safety of their country. Many of the principles that have been used were well known to the international scientific world in 1940. To develop the necessary industrial process from these principles has been costly in time, effort, and money, but the processes which we selected for serious effort have worked and several that we have not chosen could probably be made to work. We have an initial advantage in time, because, so far as we know, other countries have not been able to carry out parallel developments during the war period. We also have a general advantage in scientific and particularly in industrial strength, but such an advantage can easily be thrown away.

Before the surrender of Germany there was always a chance that Ger-

man scientists and engineers might be developing atomic bombs which would be sufficiently effective to alter the course of the war. There was therefore no choice but to work on them in this country. Initially many scientists could and did hope that some principle would emerge which would prove that atomic bombs were inherently impossible. This hope has faded gradually; fortunately in the same period the magnitude of the necessary industrial effort has been demonstrated so that the fear of German success weakened even before the end came. By the same token, most of us are certain that the Japanese cannot develop and use this weapon effectively.

Prognostication

As to the future, one may guess that technical developments will take place along two lines. From the military point of view it is reasonably certain that there will be improvements both in the processes of producing fissionable material and in its use. It is conceivable that totally different methods may be discovered for converting matter into energy since it is to be remembered that the energy released in uranium fission corresponds to the utilization of only about one-tenth of one per cent of its mass. Should a scheme be devised for converting to energy even as much as a few per cent of the matter of some common material, civilization would have the means to commit suicide at will.

The possible uses of nuclear energy are not all destructive, and the second direction in which technical development can be expected is along the paths of peace. In the fall of 1944 General Groves appointed a committee to look into these possibilities as well as those of military significance. This committee (Dr. R. C. Tolman, chairman; Rear Admiral E. W. Mills (USN) with Captain T. A. Solberg (USN) as deputy, Dr. W. K. Lewis, and Dr. H. D. Smyth) received a multitude of suggestions from men on the various projects, principally along the lines of use of nuclear energy for power and the use of radioactive by-products for scientific, medical, and industrial purposes. While there was general agreement that a great industry might eventually arise, comparable, perhaps, with the electronics industry, there was disagreement as to how rapidly such an industry would grow; the consensus was that the growth would be slow over a period of many years. At least there is no immediate prospect of running cars with nuclear power or lighting houses with radioactive lamps although there is a good probability that nuclear power for special purposes could be developed within ten years and that plentiful supplies of radioactive materials can have a profound effect on scientific research and perhaps on the treatment of certain diseases in a similar period.

Planning for the Future

During the war the effort has been to achieve the maximum military results. It has been apparent for some time that some sort of government control and support in the field of nuclear energy must continue after the war. Many of the men associated with the project have recognized this fact and have come forward with various proposals, some of which were considered by the Tolman Com-

mittee, although it was only a temporary advisory committee reporting to General Groves. An interim committee at a high level is now engaged in formulating plans for a continuing organization. This committee is also discussing matters of general policy about which many of the more thoughtful men on the project have been deeply concerned since the work was begun and especially since success became more and more probable.

The Questions Before the People

We find ourselves with an explosive which is far from completely perfected. Yet the future possibilities of such explosives are appalling, and their effects on future wars and international affairs are of fundamental importance. Here is a new tool for mankind, a tool of unimaginable destructive power. Its development raises many questions that must be answered in the near future.

Because of the restrictions of military security there has been no chance for the Congress or the people to debate such questions. They have been seriously considered by all concerned and vigorously debated among the scientists, and the conclusions reached have been passed along to the highest authorities. These questions are not technical questions; they are political and social questions, and the answers given to them may affect all mankind for generations. In thinking about them the men on the project have been thinking as citizens of the United States vitally interested in the welfare of the human race. It has been their duty and that of the responsible high government officials who were informed to look beyond the limits of the present war and its weapons to the ultimate implications of these discoveries. This was a heavy responsibility. In a free country like ours, such questions should be debated by the people and decisions must be made by the people through their representatives. This is one reason for the release of this report. It is a semi-technical report which it is hoped men of science in this country can use to help their fellow citizens in reaching wise decisions. The people of the country must be informed if they are to discharge their responsibilities wisely.

On Back Cover

➤ BURST *of the first atomic bomb at Hiroshima billowed smoke 20,000 feet into the air above the target. Photographed by U. S. Army Air Forces.*

A Committee of British Scientists Was Studying Atom Fission in 1940

Britain and the Atomic Bomb

Statement of the BRITISH GOVERNMENT.
British Information Service, 1336 New York Ave., N.W., Washington 5, D. C.

➤ AS THE COMMITTEE pointed out, an outstanding difficulty of the atomic bomb scheme is that the bomb cannot be tested on a small scale; it is all or nothing. The firmness of the Committee's conviction that it was indeed all and not nothing can be judged by their daring in putting forward a project of this magnitude, when some most essential parts of the scheme were still in the early stages.

A different but important aspect of the application of the fission of uranium was also reviewed by the Committee. This was the possibility, mentioned in a previous section of this statement, of finding conditions under which a mixture of uranium and some suitable "slowing-down" medium might give a neutron chain reaction in which the release of energy was obtained in a controlled way. This work was being carried out at Cambridge by Drs. Halban and Kowarski.

These two French physicists had been sent by Professor Joliot to Britain at the time of the fall of France in June 1940.

They brought with them the 165 liters of "heavy water"—practically the whole world stock of this material—which the French Government had brought from the Norsk Hydro Company just before the invasion of Norway. Drs. Halban and Kowarski were instructed by Professor Joliot to make every effort to get in England the necessary facilities to enable them to carry out, with the co-operation of the British Government, and in the joint interest of the Allies, a crucial experiment which had been planned in Paris and for which the "heavy water" had been acquired.

Facilities were provided at the Cavendish Laboratory, Cambridge, and, by December 1940, they produced strong evidence that, in a system composed of uranium oxide (as actually used) or uranium metal with "heavy water" as the slowing-down medium, a divergent slow neutron fission chain reaction would be realized if the system were of sufficient size.

It seemed likely that, if uranium metal were used, this critical size would involve not more than a few tons of "heavy water."

The Committee concluded that this work had great potential interest for power production but that this particular application was not likely to be developed in time for use in the war.

It was, however, recognized that the slow neutron work had a bearing on the military project, for the plutonium which would be produced in such a system could be extracted chemically and might be capable of use in an atomic bomb instead of U-235. The difficulties in the way of building a slow neutron system seemed to be prohibitive at that time.

Canada's National Research Council Administers Dominion's Contribution

Canada's Role in Atomic Drama

Statement of the CANADIAN GOVERNMENT.
Canadian Wartime Information Board, 1205 15th St., N.W., Washington 5, D. C.

CANADA has been associated with scientific development in this field since the time when Rutherford began his investigations on Radioactivity in McGill University in 1899. Investigations were, however, confined to university laboratories until the outbreak of war in 1939. From that time, the interests of scientists working on this subject in Britain, the United States, Canada and France were directed to the possibility of a practical application. On the fall of France, French scientists working on the problem were sent by Professor Joliot to join the British scientists. In October, 1940, information on this and other war research was interchanged between Britain, the United States and Canada. Towards the end of 1942, the British proposed that an important section of the work should be carried on in Canada as a joint enterprise. Accordingly a joint laboratory of United Kingdom and Canadian staff was established in Montreal under the administration of the National Research Council. This laboratory has now grown to a staff of over 340, by far the largest organization ever created in this country to carry out a single research project.

Plant at Petawawa

As a result of agreements reached between the three partner governments, the work of this laboratory was closely co-ordinated with the tremendous research activity in this field in the United States. Its work led to the design of a pilot plant for the production of atomic bomb materials, now under construction at Petawawa, Ontario, by Defense Industries Limited, as a part of the combined United Kingdom-United States-Canadian program. A branch of the National Research Council will be established there in close association with the pilot plant to carry out research on the application of atomic energy in war and in industry, and on the use of its products in research and medicine.

The primary material required for the operation of this pilot plant and for its production of materials for atomic bombs is uranium. One of the world's two most important deposits of this substance was discovered by Gilbert Labine near Great Bear Lake in Canada. To preserve this important asset for the people of Canada and to protect the supply for the United Nations, the Dominion Government took over the ownership of the mines and the extraction plant . . .

The plant which is being built near Petawawa to produce materials for release of atomic energy will contain uranium and heavy water. When these materials are brought together in certain proportions and in sufficient quantity chains of fissions are set up and large quantities of energy are released from the uranium in a controlled and non-explosive way.

The Smyth Report

➤ "NOTHING in this report discloses necessary military secrets as to the manufacture or production of the weapon. It does provide a summary of generally known scientific facts and gives an account of the history of the work, and of the role played in the development by different scientific and industrial organizations.

"The best interests of the United States require the utmost cooperation by all concerned in keeping secret now and for all time in the future all scientific and technical information not given in this report or other official releases of information by the War Department."

In these words, reminiscent of the blessing and the curse which end the Book of Revelation, the War Department speeds forth its announcement of how atomic power was tapped.

In bringing our readers this preview of the Smyth Report, the editors of CHEMISTRY have been guided by memory of their own breathless curiosity on August 10 when they first got a copy of the Report into their hands.

HOW does atomic power work? WHAT are these new elements? WHERE did they get their materials? HOW did they do it? WHAT is a nuclear chain reaction? Everything else seemed more than a little unreal.

To answer these questions in this issue of the magazine, it was necessary to change the order of the Report, which follows the chronological development of the project. We have dived in and brought up for your amazement some of the good stories which will answer those first excited questions. There are still a few left over, notably the "Chemistry of Plutonium," which will have to wait for the October and subsequent issues. We have preferred to document this issue with the President's message, which dropped a figurative bomb on the whole world, and short extracts from the official British and Canadian reports.

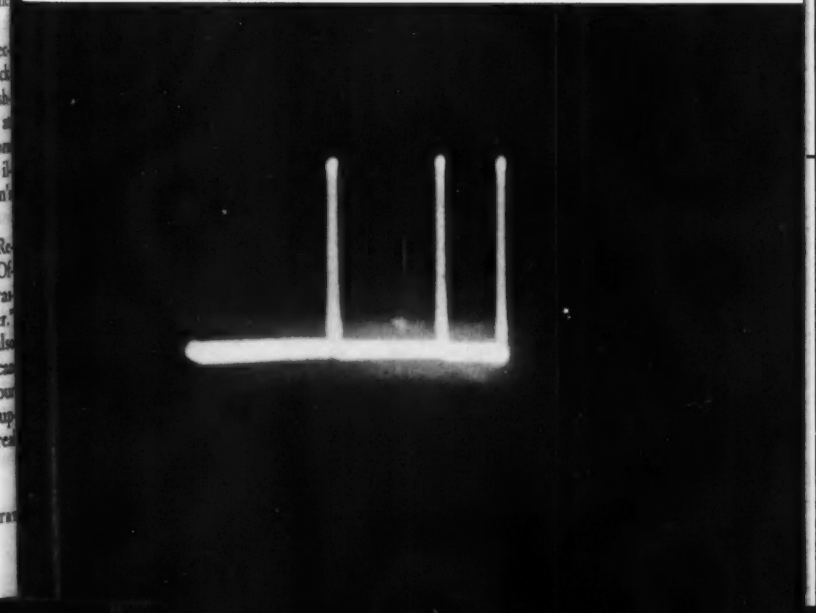
The text of this issue, it seems proper to emphasize, from page 5 through page 53, is taken verbatim from the Smyth Report, in line with the War Department's statement: "Reproduction in whole or in part is authorized and permitted."

Introductory paragraphs connecting the stories are in the editors' words, and are distinguished by being printed in italics. Titles and subtitles are so far as possible in the words of the Report.

The illustrations in the front section of the magazine and on the back cover are official photographs furnished by the War Department. Those in the back of the magazine are from the files of Science Service, and illustrate important steps in man's mastery of the atom before 1941.

Since publishing the Smyth Report, the Government Printing Office finds itself somewhat embarrassed at having produced a "best seller." Princeton University Press is also bringing out an edition. Until you can get a copy of the whole report for your library, CHEMISTRY is happy to supply you with this foretaste of a real classic of scientific literature.

THIS IS *what you see when studying atom splitting. The traces in the upper picture were made on the photographic plate by atom particles. The fork in the trail shows where an alpha particle hit the nucleus of an atom. Splitting uranium atoms releases energy which, when put into an oscillograph, makes a pattern like the one pictured below.*



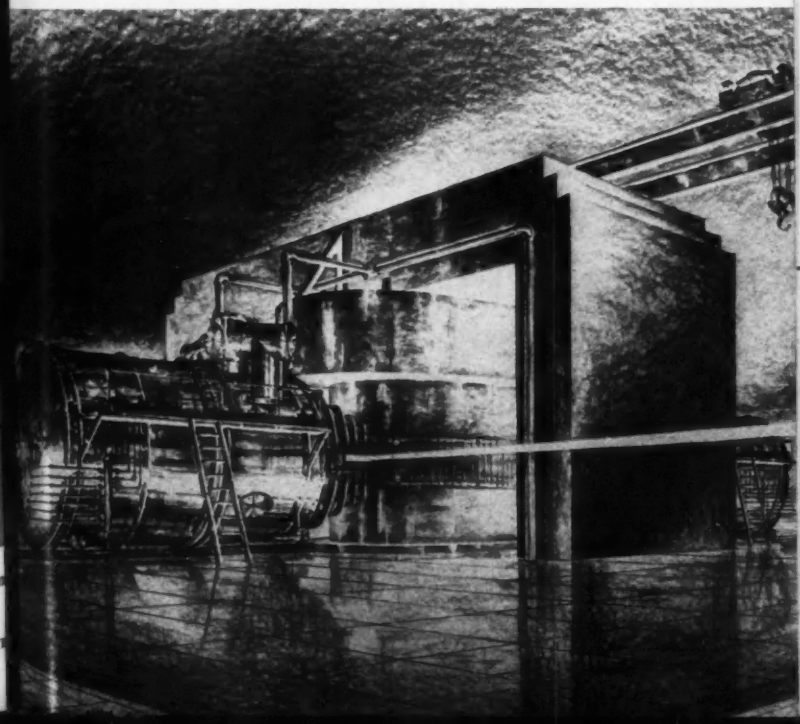
➤ Dr. E. O. Lawrence, *University of California, holds in the palm of his ha*
the beginnings of the cyclotron.

The Cyclotron

Ions speeding around the halves of a flat cylinder in the cyclotron are accelerated each time around by an additional impact of several thousand volts. They thus attain speeds equal to those that would result from some millions of volts pressure. As an ion accelerates its orbit grows larger, until it reaches the outer edge, where a deflecting blade diverts it against the desired target. Collision at such speed causes the breakdown of the atom through disruption of its nucleus.

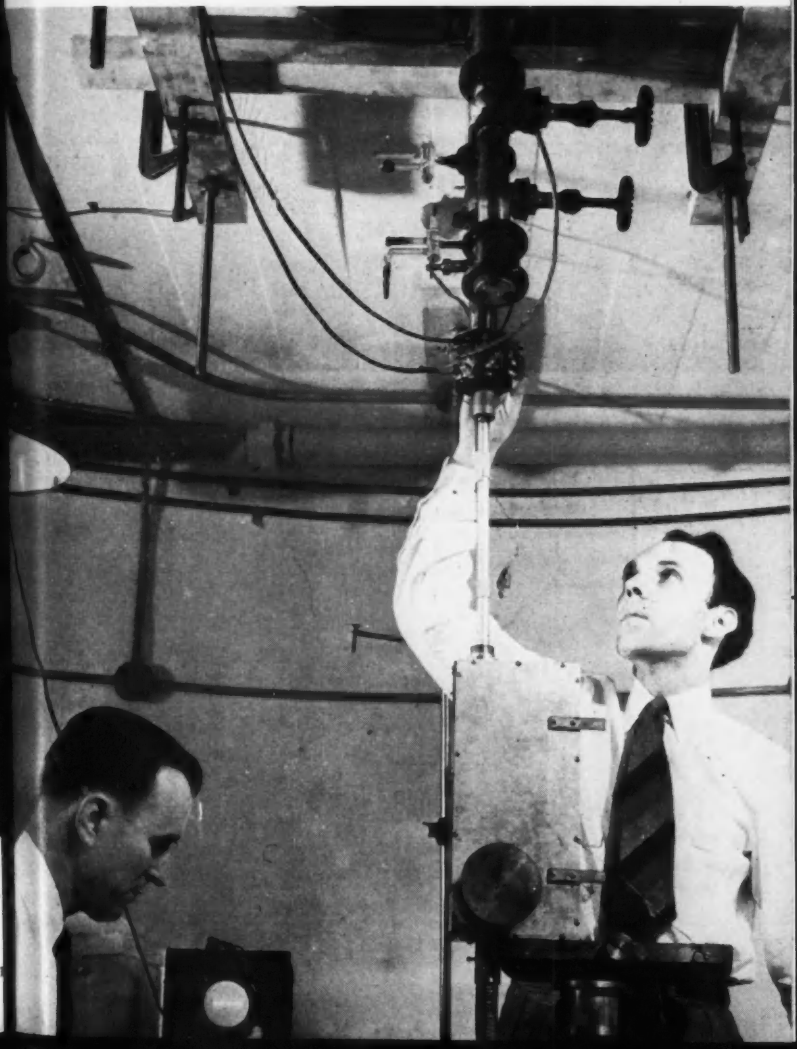
"At Berkeley," says the Smyth Report, "the 37-inch cyclotron was dismantled on November 24, 1941 and its magnet was used to produce the magnetic field required in what came to be called a 'Calutron' (a name representing a contraction of 'California University cyclotron'). An ion source consisting of an electron beam traversing the vapor of a uranium salt was set up. Ions were then accelerated to the slit through which they passed into the separating region where the magnetic field bent their paths into semicircles terminating at the collector slit."

Artist's drawing *of the 4,900 ton cyclotron, developed from the small one first made by Dr. Lawrence, which was in process of building at the University of California when the blackout of news on atomic phenomena came.*



➤ To SPEED *atom particles in their attack on atom nuclei, electrostatic sparks at 10,000,000 volts were generated by this Van de Graaff generator at Massachusetts Institute of Technology, in studies preliminary to atomic power.*

SCIENTISTS *of the Carnegie Institution, Washington, D. C., were at work on uranium fission problems before the war. In this picture, taken in 1939, Dr. Richard B. Roberts adjusts the tiny chamber where energy from uranium has just been released by a 10,000,000 volt atom smasher on the floor above. Dr. J. C. Meyer, left, watches the recording oscillograph on which the atom splitting is detected.*



▶ THE MASS SPECTROGRAPH *used for successful isolation of minute amounts of U-235 in 1940 is demonstrated by Dr. K. H. Kingdon and Dr. H. C. Pollock of General Electric Research Laboratories.*

The Mass Spectrograph

▶ IN THE mass spectrograph the gas to be studied is bombarded with a stream of electrons and so ionized. The electric charges so acquired make the gas susceptible to electric and magnetic fields. By adjustment of these fields in the apparatus, it is possible to sort out by weight the different ions present. Since the ions carry unit electric charges, the number of ions present is proportional to the electric current. The ratio of the currents carried by the different isotopes of the element present, which can be read from sensitive electric meters, is thus the ratio of the abundance of the different isotopes.

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